ERDC/CERL TR-12-11

US Army Corps of Engineers®
Engineer Research and Development Center

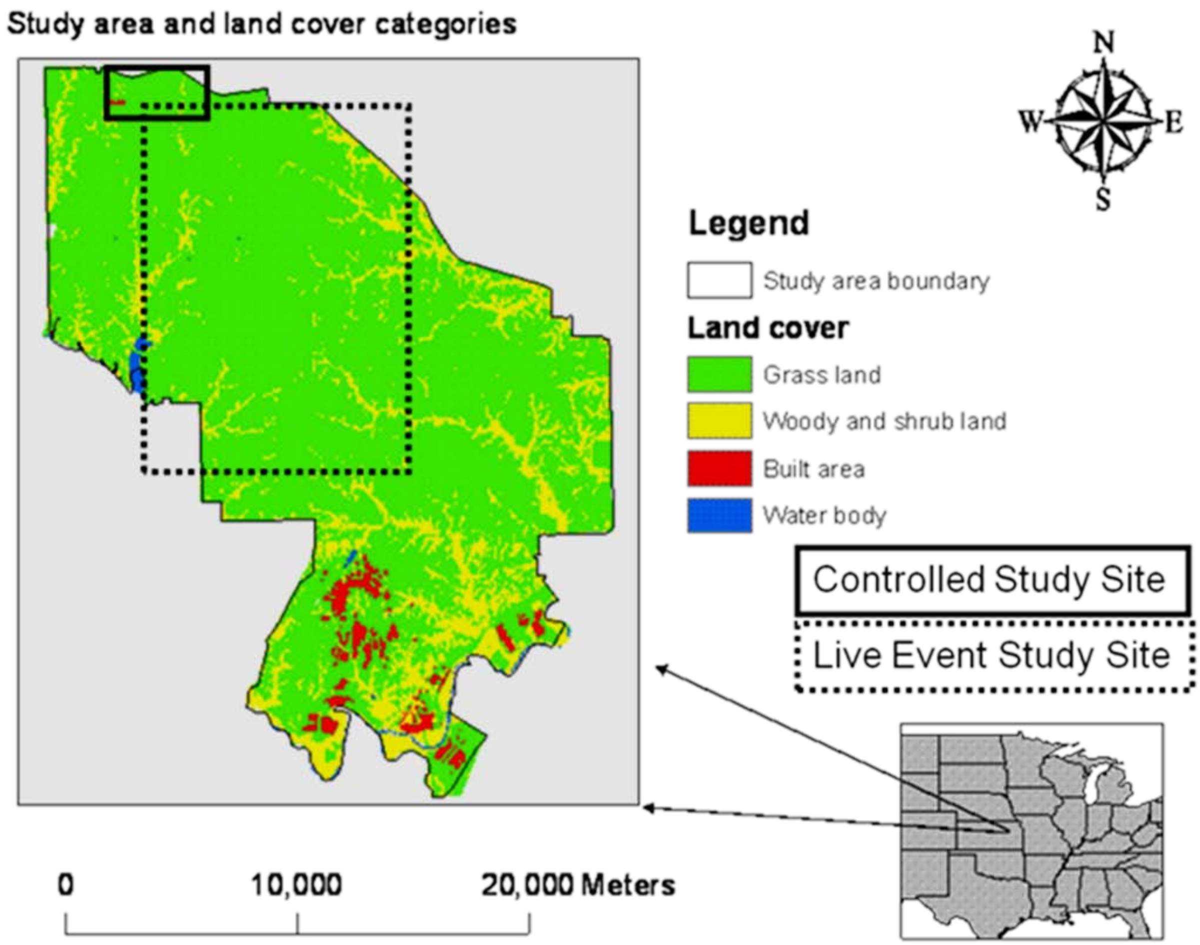
Environmental Security Technology Certification Program (ESTCP)

Vehicle Dynamics Monitoring and Tracking System (VDMTS)

Monitoring Mission Impacts in Support of Installation Land Management

Daniel J. Koch, Paul D. Ayers, Heidi R. Howard, and Gary Siebert

June 2012



Approved for public release; distribution is unlimited.

Construction Engineering Research Laboratory

Environmental Security Technology
Certification Program (ESTCP)

ERDC/CERL TR-12-11
June 2012

Vehicle Dynamics Monitoring and Tracking System (VDMTS)

Monitoring Mission Impacts in Support of Installation Land Management

Daniel J. Koch and Heidi R. Howard

Construction Engineering Research Laboratory (CERL)
US Army Engineer Research and Development Center
PO Box 9005
Champaign, IL 61826-9005

Paul D. Ayers

University of Tennessee
Knoxville, TN 37996

Gary Siebert

3885 Research Park Drive
Ann Arbor, MI 48108

Final Report

Approved for public release; distribution is unlimited.

Prepared for Headquarters, US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

The Vehicle Dynamics Monitoring and Tracking System (VDMTS) has three components: (1) vehicle impact models, (2) vehicle-tracking hardware and software, and (3) vehicle-tracking stat analysis. The vehicle-tracking approach was used to predict impacts associated with military and vehicle maneuver training. These dynamic characteristics are used to predict area impacted, vegetation loss, and rut depth based on vehicle type and location. These results are then summarized to characterize training land-use patterns and quantify the severity of the training impacts. This demonstration/validation project tested and validated each aspect of the VDMTS process. In multiple levels, it tested and demonstrated the accuracy of the hardware and models in combination, the durability of the hardware under multiple training events, the ease of use of the VDMTS process, and the ability to make land-use decisions based on the VDMTS collected and summarized data. The document provides the lessons learned from the demonstration and provides information on implementation strategies and options.

Executive Summary

The use of military vehicles during training results in soil disturbance and vegetation loss, with subsequent increases in soil erosion rates, sedimentation in streams, habitat degradation, and numerous other secondary effects. The National Environmental Policy Act (NEPA) requires Federal agencies to evaluate the implications of their plans, policies, programs, and projects. However, accurate assessment of military training impacts is limited by the technical data available to support the assessments. This project demonstrated the use of the Vehicle Dynamics Monitoring and Tracking System (VDMTS) to assess and predict military vehicle maneuver training impacts for use in land management decisionmaking and NEPA documentation. The VDMTS approach is composed of three components: (1) vehicle impact models, (2) vehicle-tracking hardware and software, and (3) vehicle-tracking data analysis. The approach spatially characterizes short-term, direct impacts by monitoring individual vehicle locations and operating characteristics. These dynamic characteristics are used to predict area impacted, vegetation loss, and rut depth based on vehicle type and location.

This demonstration/validation project tested and validated each aspect of the VDMTS process at multiple levels, specifically: accuracy of the hardware and models in combination; durability of the hardware under multiple training events; ease of use of the VDMTS process; and ability to make land-use decisions based on the VDMTS collected and summarized data. The following quantitative metrics were tested to assess each aspect of VDMTS performance: (1) accurate VDMTS hardware measurement of vehicle dynamic properties, (2) accurate VDMTS impact model predictions of site impacts under controlled conditions, (3) accurate VDMTS hardware measurement of vehicle static and dynamic properties, (4) accurate VDMTS model predictions of site impacts during live training, (5) VDMTS hardware durability (in single live training event), (6) VDMTS Hardware durability over 14 live training events, (7) ease of system use, and (8) quality and accuracy of data for land-use decisions.

The following hardware performance metrics (described above) were met: 1, 3, and 5-8. Metrics 2 and 4 (accurate VDMTS impact models predictions in controlled and live events) did not meet the success criteria initially

proposed. The demonstrated average error for disturbed width was 14.9 cm and the average error for vegetation removal was -1.8%. These results are comparable with existing site and vehicle-specific empirical model predictions, thus reducing the need to develop models for each site. This validates the use of the theoretical models for impact prediction.

Overall, the demonstration and validation project confirmed that a need exists for a system that can produce data and analyses like the VDMTS. The system met most of the metrics established. While it failed to meet some metrics, it still performed as well as previous methods in characterizing vehicle impacts, reducing the relative cost and time required.

This work was undertaken to assist installations in making informed decisions regarding technology implementation and associated costs. The resulting technology is valuable in obtaining data to estimate impacts from military training. Through the course of the project, installation Integrated Training Area Management (ITAM), Environmental, Directorate of Public Works (DPW), and training groups used results obtained from this study. Data collected were used in land management and vehicle mobility and power models. Study results also informed training and regulating decisions.

Table of Contents

List of Figures and Tables

Figures

Tables

Preface

This demonstration project was conducted for the US Department of Defense's (DoD's) Environmental Security Technology Certification Program (ESTCP) under Project RC-200815, "Vehicle Dynamics Monitoring and Tracking System: Monitoring Mission Impacts in Support of Installation Land Management." The technical monitors were Dr. Jeffrey Marqusee, ESTCP Director, and Dr. John Hall, ESTCP Resource Conservation and Climate Change Program Manager.

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CN), and the Office of the Technical Director (OTD), Construction Engineering Research Laboratory (ERDC-CERL). Daniel J. Koch was the ERDC-CERL Principal Investigator (PI). Dr. Paul Ayers is affiliated with the Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville; Gary Seibert is associate with Cybernet Systems Corp. Thanks is owed to HydroGeoLogic, Inc., contractor for the ESTCP program, including John Thigpen, Carrie Wood, Kristen Lau, Lucia Valentino, Sheri Washington, Jennifer Rusk, Susan Walsh, Pedro Morales, Badrieh Sheibeh, and Daniel Ruedy for their technical and administrative support. Individuals recognized for their assistance and support each installation are Dr. Phil Woodford, Tim Marston, Dave Faucette, and Kevin Sura, which helped coordinate the studies at each installation; and Chris Otto, Troy Livingston, Monte Cales, John Brent, Gary Hollon, Charles Grantham, Chad Camp, Johnny Markham, Terry Jones, Hugh Westbury and Brett Rodomsky. PIs on other Strategic Environmental Research and Development Program (SERDP)/ESTCP projects that provided data and comments for this project include Dr. Stacy Hutchinson and Dr. Shawn Hutchinson (RC-200820), Dr. Lisa Rew and Dr. Hal Balbach (RC-1545), and Anthony Donigian (RC-1547). William Meyer is Chief, CEERD-CN-N. Dr. John Bandy is Chief, CEERD-CN. Alan Anderson is Technical Director, CEERD-CV-T. The Director of ERDC-CERL is Dr. Ilker R. Adiguzel.

CERL is an element of the US Army Engineer Research and Development Center (ERDC), US Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Kevin J. Wilson, and the Director of ERDC is Dr. Jeffery P. Holland.

1 Introduction

1.1 Background

The Vehicle Dynamics Monitoring and Tracking System (VDMTS) consists of three components: (1) vehicle impact models, (2) vehicle-tracking hardware and software, and (3) vehicle-tracking data analysis.

The VDMTS approach was developed to predict impacts associated with vehicle-based training. The approach spatially characterizes short-term, direct impacts resulting from vehicles by monitoring individual vehicle locations and operating characteristics (e.g., turning radius and velocity). Vehicle impact models are used to predict area impacted, vegetation loss, and rut depth, and are based on vehicle-operating characteristics and location. Analysis routines are used to summarize use patterns and the severity of cumulative impacts.

The vehicle impact models are theoretical, process-based vehicle impact models used to predict site impacts in terms of disturbed area, vegetation loss, and rut depth. Process-based impact models predict severity of impact based on vehicle static properties (e.g., vehicle type, weight, dimension), vehicle dynamic properties (e.g., turning radius, velocity), and site conditions (e.g., soil strength). Data collected by the VDMTS hardware are used with the impact models to predict spatially explicit site impacts.

The vehicle-tracking hardware and software measure vehicle kinematics, dynamics, and other parameters of interest. This enables accurate modeling of environmental impacts. Innovative sensor fusion software combines data from these sensors to provide position information even during global positioning system (GPS) outage. The system thereby provides vehicle dynamics data and positional information at all times, even when GPS is unavailable. The VDMTS has the capability to record the vehicle dynamics tagged with position information for post-mission analysis. Vehicle-tracking visualization software resides on a user's desktop that provides simple visual access to the VDMTS data within a geographic information system (GIS) environment.

Vehicle-tracking data analysis routines summarize vehicle-tracking data in a manner compatible within typical installation decisionmaking processes. Analysis routines include spatial displays of estimated vegetation loss and soil rutting, percent of vegetation lost within management areas, percent on and off-road traffic, potential trail identification, training patterns, and vehicle training in proximity to Threatened and Endangered Species (TES) habitat.

NEPA requires Federal agencies to evaluate the environmental implications of their plans, policies, programs, and projects — at the same time that traditional economic and technical evaluations are underway. The deployment of new weapon systems or operational changes in training requires an evaluation of potential impacts on installation natural resources, and the evaluation of mitigations to alleviate their effects. The use of military vehicles during training results in soil disturbance and vegetation loss, with subsequent increases in soil erosion rates, sedimentation in streams, habitat degradation, and numerous other secondary effects. The capacity of installation lands to support training activities is a function of both the sensitivity of lands to specific activities and the natural recovery rates of vegetation. However, it is also a function of weapon system characteristics, the doctrine that establishes how these systems are used, and the actual locations where activities are conducted. Accurate assessment of these impacts is limited by the technical data available to support the assessments.

The impact of off-road vehicle use on soil and vegetation has been extensively studied (Demarais et al. 1999, Anderson et al. 2005a). However, multiple factors (Morrison-Saunders and Bailey 2003) have limited the effective use of this information in environmental impact assessments. These factors include vehicles having multiple configurations, assessments that involve multiple vehicle types, and a lack of understand of how and where vehicle are used in the natural landscape. For example, individual weapon systems are often fielded in more than one configuration, each with unique static vehicle properties. Consider that: (1) the Stryker vehicle comes in eight configurations varying in weight from 28,000 lbs to 41,000 lbs, (2) new weapon systems are not fielded independently of other vehicles, and (3) multiple vehicle types make individual military units. Therefore, the assessment of new weapon systems or relocation of existing units requires comparison between different units, each made up of varying vehicle types and/or configurations. Information sources that fail to account

for these factors provide limited and often misleading information on the range of impacts associated with vehicle training activities.

One common approach to assess impacts of vehicles has been to measure historically disturbed and undisturbed sites (Johnson 1982, Shaw and Diersing 1990, Milchunas et al. 1999, Milchunas et al. 2000, Anderson et al. 2005b). While these studies are useful for quantifying the cumulative impact of vehicle tracking on vegetation, they provide little quantitative information that relates type and level of vehicle use to the amount of vegetation damage. A second approach to assess impacts of vehicles has been to conduct controlled studies quantifying the impact of specific vehicles at specified levels of use (Payne et al. 1983, Wilson 1988, Thurow et al. 1995, Prosser et al. 2000, Grantham et al. 2001). Typically, these replicated studies involved repeated tracking of study plots with a specific vehicle. However, it is not clear if the dynamic vehicle properties used in these studies are representative of actual site use or include the most damaging vehicle activities. A third approach to assess impacts of vehicles is to use models (Shaw and Diersing 1989, Anderson et al. 1996, Childress et al. 2002) to predict impacts. These capacity models require input data on the distribution and severity of vehicle impacts. Information on distribution and severity of vehicle impacts is generally lacking.

As a result of the SERDP project "Improved Units of Measure for Training and Testing Area Carrying Capacity Estimation" (Anderson 1999, SERDP RC-1102), and the Army Small Business Innovative Research (SBIR) project, "Enhanced GPS/INS Tracking and Vehicle Dynamics Monitoring System," an approach and tool set have been developed to collect timely, relevant, and consistent vehicle impact data to effectively support NEPA and other land management requirements. The approach addresses the spatial distribution of impacts, severity of impact for most military vehicles, and accounts for how vehicles are used during training. The approach uses vehicle-tracking systems to determine vehicle location and dynamic operating characteristics (e.g., turning radius and velocity).

Impacts models are used with the vehicle data to predict site impacts. Vehicles are initially operated through defined courses to establish a range of vehicle dynamic operating conditions. Impacts associated with vehicle use are measured along the course, and models are developed from the field data to predict vehicle impacts. Vehicle-tracking systems are used to track

vehicles in live training exercises. Location and vehicle property information are used with the impact models to predict the cumulative impact of training exercises. The approach strengthens the scientific basis for NEPA analyses, leading to more sustainable Army decisions.

After a decision to field weapon systems is made at an installation, vehicle-tracking systems provide both a new capability and a proactive means for the installation to monitor land condition and preemptively implement Land Repair and Maintenance (LRAM) programs. Traditional methods for site evaluation and monitoring based on permanent field plots are costly, time consuming, and potentially unreliable. Current DoD Land Condition Trend Analysis (LCTA) programs suffer from lag times between field data collection, site prioritization, and initiation of LRAM projects. The direct monitoring of mission impacts allows land managers to locate the most severe impacts after training events and to mitigate initial site damage before lands further degrade.

A demonstration and validation project was required to assess and quantify the overall performance, durability, and utility of the proposed system under operational field conditions to address a range of DoD land management problems. Land management applications include: (1) development of data for carrying capacity models, (2) early identification of trail formation, (3) identification and prioritization of LRAM sites, (4) collection of data to support NEPA processes, (5) characterization of training patterns within TES habitat, (6) road condition assessment, and (7) collection of data for impact analysis.

1.2 Regulatory drivers

NEPA requires Federal agencies to evaluate the environmental implications of their plans, policies, programs, and projects, at the same time that traditional economic and technical evaluations are underway. NEPA requires that an Environmental Impact Statement (EIS) include descriptions of the relationship between short-term uses of the environment and maintenance of long-term ecological productivity. For military weapon systems and training activities, EIS require descriptions of the impact of weapon systems and training on installation resources. The completion of the NEPA process often results in agreement by the DoD to monitor im-

pacts and assess EIS assumptions. The proposed VDMTS approach provides improved methods and tools to meet NEPA requirements.

The Federal Water Pollution Control Act, commonly referred to as the Clean Water Act (CWA), is intended to restore and maintain the chemical, physical, and biological integrity of the nation's waters by preventing point and nonpoint pollution sources. Nonpoint source (NPS) pollution comes from many diffuse sources like military lands. NPS pollution is caused by rainfall or snowmelt moving over and through the ground. As the runoff moves, it picks up and carries away natural and human-made pollutants, finally depositing them into the nation's waters.

Some waters in the nation do not meet the CWA national goal of "fishable, swimmable" despite the fact that nationally required levels of pollution control technology have been implemented by many pollution sources. CWA Section 1313 addresses waters that are not "fishable, swimmable" by requiring states to identify the waters and to develop total maximum daily loads (TMDLs) for them, with oversight from the US Environmental Protection Agency (40 CFR 130.7). As such, TMDLs play a key role in watershed management.

Each state identifies waters at risk and establishes TMDLs to protect those waters. This includes identifying required load reductions within a watershed from agricultural, military and other nonpoint sources. These load reductions are achieved through nonpoint source programs established under CWA Section 319. Soil erosion and the resulting siltation of waterways has long been a major concern on military installations. Off-road-vehicle-based maneuver training is a major contributor to accelerated erosion on military lands. This erosion and the associated sedimentation of surrounding waterways can be in violation of the CWA. It has been previously estimated that the cost to restore damage Army lands to tolerable levels of soil erosion could range from $100M to $200M per year for up to a decade (Warren et al. 2000).

Section 7 of the Endangered Species Act (ESA) requires Federal agencies to ensure that the actions they take, including those they fund or authorize, do not jeopardize the existence of any listed species. If a Federal agency determines that an action may adversely affect a listed species, the agency must submit to US Fish and Wildlife Service (USFWS) a request for

consultation. During consultation, the USFWS and Federal agency share information about the proposed project and the species likely to be affected. The USFWS provides a biological opinion on whether the proposed activity jeopardizes the continued existence of a listed species. In making a determination on whether an action results in a jeopardy, the USFWS looks at the current status of the species (baseline). The USFWS considers direct, indirect, interrelated, interdependent, and cumulative effects. The burden is on the Federal agency to fund activities related to ESA including providing data for the USFWS determination. Thus, if a Federal agency action is important (e.g., live training), the motivation is for the Federal landowner to provide data to support their position. Direct/indirect/other effects studied are primarily those that are military unique impacts not likely to be funded by other organizations. The burden is on the Army to prove beyond a reasonable doubt that Army actions are not a cause for concern.

1.3 Objectives

The objective of this project was to demonstrate and validate the VDMTS system and its components through a series of controlled field studies and live tracking events.

1.4 Approach

A controlled field study was used to demonstrate and validate that the hardware can sufficiently characterize vehicle dynamic properties (turning radius and velocity) to accurately predict site impacts (i.e., area impacted, vegetation loss, and rut depth). A controlled field study was used to demonstrate and validate the accuracy of VDMTS impact models in predicting area impacted, vegetation loss, and rut depth for a range of vehicles. Field studies tracking live training exercises and subsequent field measurements were used to demonstrate and validate the VDMTS hardware and model performance in predicting site impacts.

1.5 Mode of technology transfer

This report will be made accessible through the World Wide Web (WWW) at URLs:

http://www.cecer.army.mil

http://libweb.erdc.usace.army.mil

2 Technology/Methodology Description

This chapter describes the VDMTS vehicle-based maneuver impact assessment process and the technology and theoretical models that the system uses. This chapter also summarizes the advantages and disadvantages of using the VDMTS process rather than alternative technologies.

2.1 Technology/methodology overview

The VDMTS approach is used to assess and predict impacts resulting from military vehicle-based maneuver training. The approach consists of vehicle impact models, vehicle-tracking hardware and software, and vehicle-tracking data analysis. The following sections discuss each component of the VDMTS approach in more detail.

2.2 Vehicle-tracking processes

Figure 1 shows the VDMTS process, which uses vehicle-tracking systems to determine vehicle location and dynamic operating characteristics (e.g., turning radius and velocity). Impact models predict site impacts based on vehicle static properties (e.g., vehicle weight and type), vehicle dynamic properties, and soil properties (soil strength). Analysis routines summarize data in formats appropriate for land management decisions.

The VDMTS vehicle hardware consists of a GPS receiver integrated with micro electro mechanical systems (MEMS) based strap-down inertial sensors (Cybernet Systems 2004, Cybernet Systems 2002). These sensors enable measurement of vehicle kinematics, dynamics and other parameters of interest. The associated VDMTS software combines data from these sensors to provide improved position information even during GPS outage. The activity characterization step of Figure 1 shows this VDMTS system component. VDMTS hardware systems have been developed and are ready for demonstration and validation. Alternative methods such as custom-built vehicle-tracking systems with commercial off-the-shelf components and military standard training systems (Army Blue Force Tracker [BFT] and National Guard Deployable Force-on-Force Instrumented Range System [DFIRST]) could also be used to collect the vehicle dynamic operating characteristics (Anderson et al. 2009, Svendsen et al. 2011).

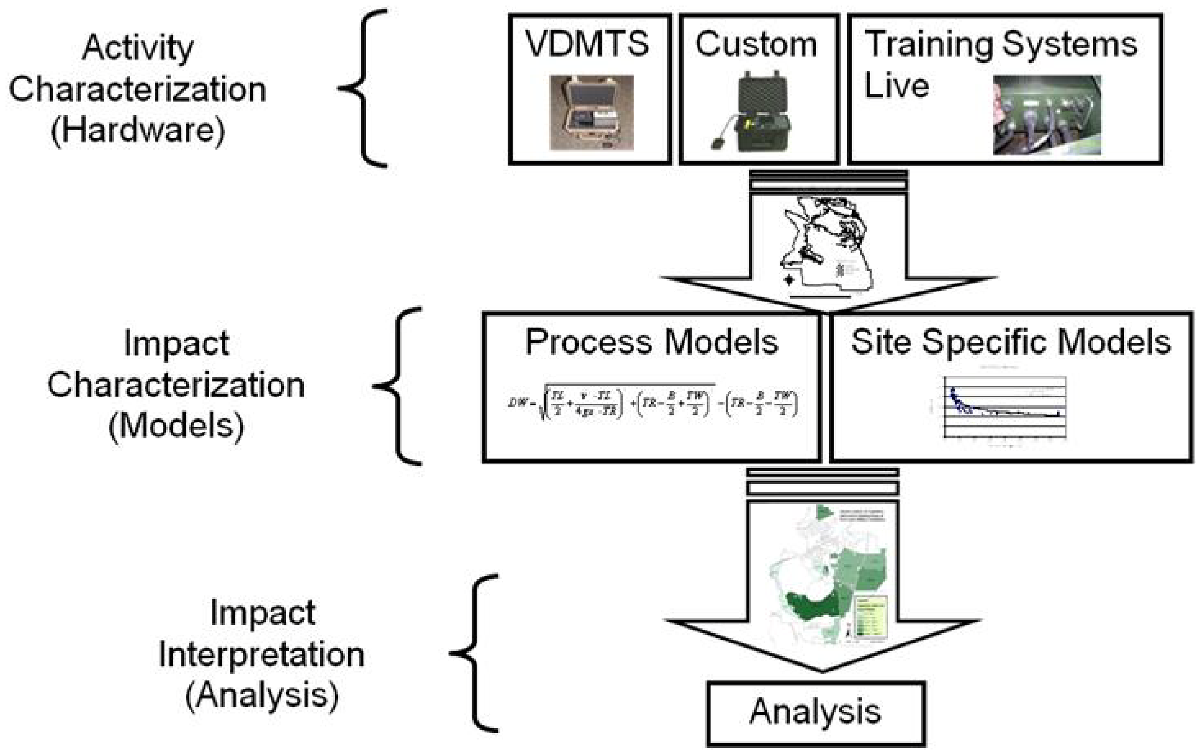


Figure 1. Vehicle-tracking and impact analysis approach.

Process-based vehicle impact models were developed through a series of controlled replicated studies (Ayers et al. 2005, Ayers et al. 2006, Foster et al. 2006, Haugen et al. 2003). Vehicles were initially operated through defined courses to establish impacts over a range of vehicle dynamic operating conditions. Impacts associated with vehicle use were measured along the course. Impact models were developed from the field data (Li et al. 2007a; Li et al. 2007b). Impact models were validated using a series of field studies of similar design for a range of ecosystems including grasslands and deserts (Li et al. 2007a; Li et al. 2007b). The Impact Characterization step shown in Figure 1 indicates the process-based impact models. An alternative method of determining impacts is to implement the system used prior to the development of the theoretical models, i.e., perform field impact assessments and develop site-specific regression models.

VDMTS vehicle-tracking systems are used to track vehicles during live training exercises. Location and vehicle dynamic property information from the VDMTS hardware are used with the impact models to predict the cumulative impact of training exercises. VDMTS data analysis routines are used to post-process tracking data. Analysis routines include spatial displays of estimated vegetation loss and soil rutting, percent of vegetation

lost within management areas, percent on and off-road traffic, and potential trail identification (Anderson et al. 2007, Ayers et al. 2005, Haugen et al. 2003, Rice et al. 2006, Wu et al. 2004, Wu et al. 2006, Wu et al. 2007).

The VDMTS process could strengthen the scientific basis for NEPA analyses and other land management decisionmaking processes leading to more sustainable Army decisions. The VDMTS process provides spatially explicit information on vehicle impact severity in usable formats.

2.2.1 Vehicle impact models

The process-based impact models predict terrain impacts caused by wheeled and tracked vehicles in terms of percent vegetation cover loss (impact severity), disturbed width, and rut depth. Percent vegetation loss is the primary measure of site impact because it is a primary variable used in Army operational monitoring programs and an input variable to many ecological models. Disturbed width is required to convert linear distance traveled to an area impacted. Rut depth is estimated because this variable is highly correlated with vegetation recovery rates and is important to models that incorporate micro-topography.

Process-based, theoretical models were developed to estimate disturbed width based on vehicle type, vehicle dynamic properties, and vehicle static properties. Disturbed width allows for the conversion from a linear distanced tracked by the VDMTS hardware to an area impacted. Individual models were developed for tracked vehicles and for four, six, and eight-wheeled vehicles. Equation 1 describes the disturbed width model for tracked vehicles. The full derivation of the tracked model can be found in Li et al. (2007b).

$$\boldsymbol{DW} = \sqrt{\left(\frac{TL}{2} + \frac{v^2 \cdot TL}{4g\mu_1 \cdot TR}\right)^2 + \left(\boldsymbol{TR} - \frac{B}{2} + \frac{TW}{2}\right)^2} - \left(\boldsymbol{TR} - \frac{B}{2} - \frac{TW}{2}\right) \qquad \text{Eq 1}$$

where:

DW = disturbed width, [m]
TR = turning radius, [m]
TL = track length, [m]
TW = track width, [m]
B = tread width, [m]

v = velocity of the vehicle, [m/s]
g = acceleration of gravity, [m/s^2]
μ_1 = coefficient of lateral resistance, [unitless].

In Equation 1, track width (TW) is a vehicle property and is the width of a single vehicle track on the vehicle. Tread width (B) is a vehicle property and is the distance between the center points of each of the two tracks on a vehicle. Tread width (B) can be thought of as the effective width of the vehicle. Disturbed width (DW) is a site property and is the width of the contact area on the ground that is disturbed by a vehicle. It is expected that for a vehicle moving in a straight line, the DW should equal the TW. As the vehicle turns, the DW should become wider than the vehicle TW. The Tread width (B) is one factor that helps determine the relationship between DW and TW. The coefficient of lateral resistance (μ_1) is a site factor that affects DW (Wong 2001).

A similar process-based, theoretical model was developed for DW from wheel vehicles. Li et al. (2007a) document DW equations and their derivation for wheeled vehicles. Equations 2 to 12 illustrate the general format for a four-axled DW model. Figure 2 schematically shows the geometric relationship of the variables for one side of the four-axled vehicle.

$$R_f = \frac{L \cdot \sin\left(\frac{\pi}{2} - \alpha_r\right)}{\sin\left(\frac{L}{TR - B/2}\right)} \quad \text{Eq 2}$$

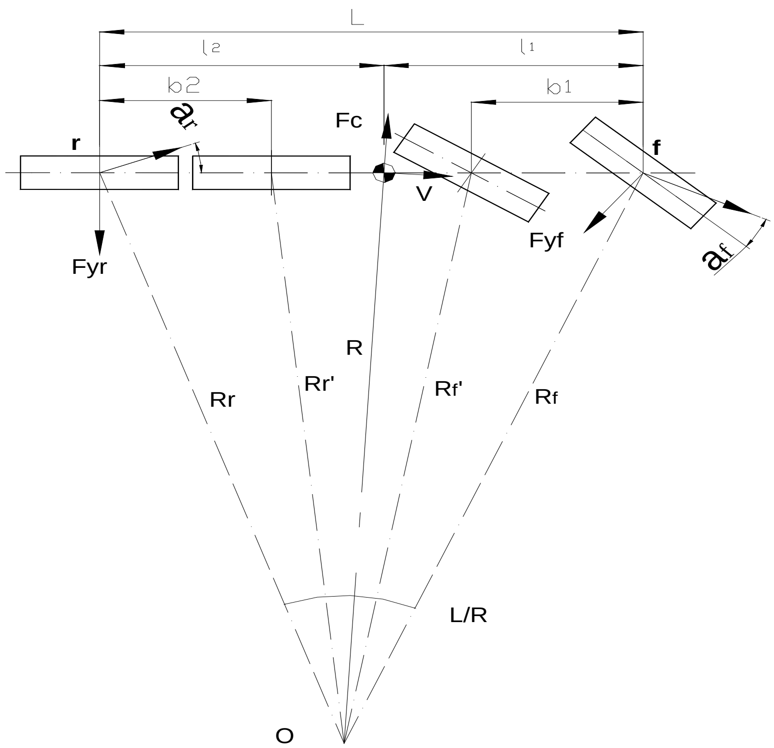
$$R_f' = \frac{(L - b_1) \cdot \sin\left(\frac{\pi}{2} - \alpha_r\right)}{\sin\left(\frac{L - b_1}{TR - B/2}\right)} \quad \text{Eq 3}$$

$$R_r = \frac{L \cdot \sin\left(\frac{\pi}{2} + \alpha_r - \frac{L}{TR - B/2}\right)}{\sin\left(\frac{L}{TR - B/2}\right)} \quad \text{Eq 4}$$

$$R_r' = \frac{(L - b_2) \cdot \sin\left(\frac{\pi}{2} + \alpha_r - \frac{L}{TR - B/2}\right)}{\sin\left(\frac{L - b_2}{TR - B/2}\right)} \quad \text{Eq 5}$$

Where (see Figure 2 for schematic of variables):

R = lengths from tire center to vehicle turning center, [m]
L = wheelbase, [m]
α_r = slip angle of rear tire, [°]
α_f = slip angle of front tire, [°]
TR = turning radius, [m]
b_1 = distance between front two tires, [m]
b_2 = distance between rear two tires, [m].



Modified from Li et al. (2007b)

Figure 2. Eight-wheeled geometric relation and dynamic conditions.

R_f, R'_f, R_r, and R'_f are ranked into R_1, R_2, R_3, and R_4 so $R_1 \geq R_2 \geq R_3 \geq R_4$. When the vehicle is going straight ahead, each tire track completely overlaps the front tire track. In this case, DW is equal to the TW. However, when the vehicle begins to turn, the rear tire tracks move away laterally from front tire track (Figure 3). Equations 6 to 12 describe the relationships between DW, TW, DW_1, DW_2 and DW_3, R_1, R_2, R_3, and R_4.

$$DW = DW_1 + DW_2 + DW_3 \qquad \text{Eq 6}$$

where:

$$DW_1 = 1.5 \cdot TW \text{ if } R_1 - R_2 \geq TW \qquad \text{Eq 7}$$

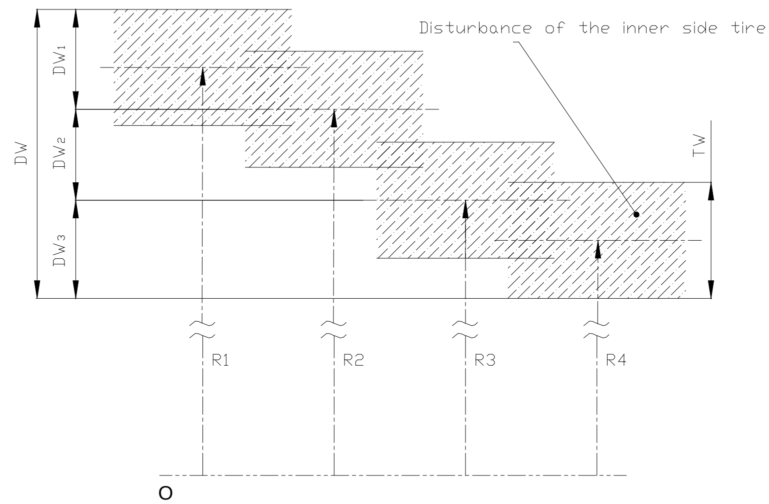
$$DW_1 = R_1 - R_2 + 0.5 \cdot TW \text{ if } R_1 - R_2 < TW \qquad \text{Eq 8}$$

$$DW_2 = TW \text{ if } R_2 - R_3 \geq TW \qquad \text{Eq 9}$$

$$DW_2 = R_2 - R_3 \text{ if } R_2 - R_3 < TW \qquad \text{Eq 10}$$

$$DW_3 = 1.5 \cdot TW \text{ if } R_3 - R_4 \geq TW \qquad \text{Eq 11}$$

$$DW_3 = R_3 - R_4 + 0.5 \cdot TW \text{ if } R_3 - R_4 < T \qquad \text{Eq 12}$$



Modified from Li et al. (2007b)

Figure 3. Scenario of relationship between DW, R_1, R_2, R_3, and R_4.

Process-based theoretical models were developed to estimate percent vegetation loss based on vehicle type, vehicle dynamic properties, and vehicle static properties. Individual models were developed for tracked vehicles and for four, six, and eight-wheeled vehicles. Equation 13 shows the vegetation loss model for tracked vehicles. The full derivation of the tracked model can be found in Li et al. (2007b). Loss of vegetation is mainly ascribed to the shear displacement of the vegetation cover and the surface soil. Higher shear stresses produced at the terrain surface result in more shear displacement and consequently, greater vegetation loss. The vegetation cover and the surface soil are completely scraped away when the shear stress reaches the maximum strength that the soil can sustain.

$$IS = \left(1 - e^{-j/K-0.233}\right) \times 100\% \qquad \text{Eq 13}$$

where:

IS = vegetation loss (impact severity), [%]
j = shear displacement, [m]
K = the shear deformation modulus, [m]
E = approximately 2.718.

The value of K depends on site conditions including soil type, soil moisture, and site vegetation. Based on experimental data, Table 1 lists K-values for some representative soil types under certain conditions (Koolen and Kuipers 1983, Kogure et al. 1982, Wong 1980, ASAE 1999).

Table 1. K-values of different soil types.

Soil type and conditions	K value (cm)
Firm sandy terrain	1
Loose sand	2.5
Clay at maximum compaction	0.6
Undisturbed, fresh snow	2.5-5
Organic soil with a mat of living vegetation on the surface and saturated peat below	14.4-16.4

Cone index (also cone penetration resistance) is a soil property that indicates the strength of a soil and is a function of the in situ soil type, moisture condition, and vegetation. K-values are empirically derived from cone index. Cone index is a standard soil test methodology commonly used to quantify soil strength in other soil rutting and trafficability models currently used by the DoD (Ahlvin and Haley 1992). Lower cone index values are associated with lower K-values. Lower K-values are associated with higher impacts for a given turning radius.

Using cone index to quantify soil strength has several advantages. First, values can be measure directly in the field with limited effort. Second, soil strength can be predicted using the Unified Soil Classification System (USCS) and soil moisture. The USCS is based on classifying soils according to their textural and plasticity characteristics. USCS classifications are readily available for national and internationally mapped soils. If soil moisture is not known or measured in the field, the Soil Moisture Strength Prediction Model Version II (SMSP II) (Sullivan et al. 1997) provides equations to predict soil moisture and soil strength based on climatic data.

Li et al. (2007a) document vegetation loss equations and their derivation for wheeled vehicles. A critical velocity, v_{cri}, is derived by balancing soil friction forces with centrifugal forces (Equation 14). The critical velocity is defined as the vehicle speed where soil shear stress is equal to the soil shear strength. The vegetation loss is calculated from a ratio of actual vehicle velocity to the critical velocity (Equation15). Any increase in velocity beyond the critical velocity results in the vehicle sliding laterally and complete vegetation removal (Equation 16).

$$v_{cri} = \sqrt{\frac{TR \cdot (c \cdot A + mg \cdot \tan\phi)}{m}} \qquad \text{Eq 14}$$

where:

v_{cri} = critical velocity, [m/s]
c = soil internal cohesion, [Pa]
A = tire-terrain contact area, [m^2]
m = vehicle mass, [kg]
g = acceleration of gravity, [m/s^2]
ϕ = internal friction angle of soil [°].

$$IS = \left(\frac{v}{v_{cri}}\right)^2 \times 100 \text{ if } v \le v_{cri} \qquad \text{Eq 15}$$

$$IS = 100 \text{ if } v > v_{cri} \qquad \text{Eq 16}$$

where:

IS = Impact severity, [%]
v = vehicle velocity, [m/s]
v_{cri} = critical velocity, [m/s], calculated in Equation 14.

Impact models being demonstrated and validated incorporate current land condition as vegetation cover. Predicted condition is based on vegetation loss from the prior condition. Each pass of a vehicle is treated as a single event with an estimated loss in vegetation. Multiple pass traffic is predicted for each pass as a single pass, but with the initial vegetation condition being the vegetation remaining from the prior pass. These models are predictive in two respects. First, vegetation loss is not measured in the field, but is predicted based on vehicle characteristics (static and dynamic) and site conditions (soil strength). Second, predictions can be made for other site conditions (e.g., wetter or dryer conditions). Using the same live event tracking data, predictions can be made for vegetation loss in wet soils, even if the event may have occurred during dry conditions. This prediction assumes that wet conditions do not change the pattern of vehicle training, only the magnitude of vegetation loss.

Rut depth or sinkage models have been developed by the US Army Engineering Research and Development Center (ERDC). The Vehicle Terrain Interface (VTI) is a vehicle terrain interaction model that predicts sinkage for vehicles in different soil conditions (Richmond et al. 2004: Jones et al. 2007, Nunez et al. 2004). However, vehicle-operating characteristics (TR

and velocity) are not inputs in this model. Liu et al. (2010) modified the VTI model to incorporate weight shift due to changes in TR and velocity (Equations 17 to 20).

$$\left(\frac{Z}{d}\right)_p = \frac{14}{\frac{G(bd)^{\frac{3}{2}}}{b_0(w_s+b_1kw_d+b_2F_c)}\cdot\frac{\delta}{h}\cdot\frac{1}{1+b/d}} \quad \text{Eq 17}$$

$$\left(\frac{Z}{d}\right)_u = \frac{22}{\left(\frac{G(bd)^{\frac{3}{2}}}{b_0(w_s+b_1kw_d+b_2F_c)}\cdot\frac{\delta}{h}\cdot\frac{1}{1+b/d}\right)^{\frac{9}{8}}} \quad \text{Eq 18}$$

$$F_c = \frac{mV^2}{TR} \quad \text{Eq 19}$$

$$W_d = \frac{2F_cH_{cg}}{TW} \quad \text{Eq 20}$$

where:

$(Z/d)_p$ = sinkage coefficient for powered wheels
$(Z/d)_u$ = sinkage coefficient for unpowered wheels
Z = sinkage for one wheel
G = cone index gradient
b = tire section width
d = nominal wheel diameter
h = tire section height
δ = tire deflection
w_s = weight shift from outside tire to inside tire
F_c = centripetal (lateral) force
b_0, b_1, and b_2 = turning force value parameters
k = indicator of wheel location (1 for outside, -1 for inside)
m = mass of vehicle supported by single wheel
V = vehicle velocity
TR = vehicle turning radius
H_{cg} = vertical distance to vehicle center of gravity
TW = tread width.

Lui et al. (2010) document the development and use of the TR modified sinkage models. This study demonstrated the use of the TR modified sinkage model against the sinkage model without turning radius modification. Richmond et al. (2004), Jones et al. (2007), and Nunez et al. (2004) document the non-modified sinkage model.

2.2.2 Vehicle-tracking hardware and software

A low-cost VDMTS was developed to automate and enhance the process of understanding the spatial and temporal characteristics of vehicle-based impacts for assessing land condition, estimating land capacity, and restoring lands in support of DoD training requirements (Figures 4 and 5). The VDMTS hardware consists of a GPS receiver integrated with low-cost MEMS-based strap-down inertial sensors. These sensors enable measurement of vehicle kinematics, dynamics and other parameters of interest that enable accurate modeling of environmental impact. Innovative sensor fusion software combines data from these sensors to provide position information even during GPS outage. The system thereby provides vehicle dynamics data and positional information at all times, even when GPS is unavailable. The VDMTS has the capability to record the vehicle dynamics tagged with position information for accurate and enhanced post-mission analysis at substantially reduced costs. Onboard system data storage provides archival data for post training event analysis.

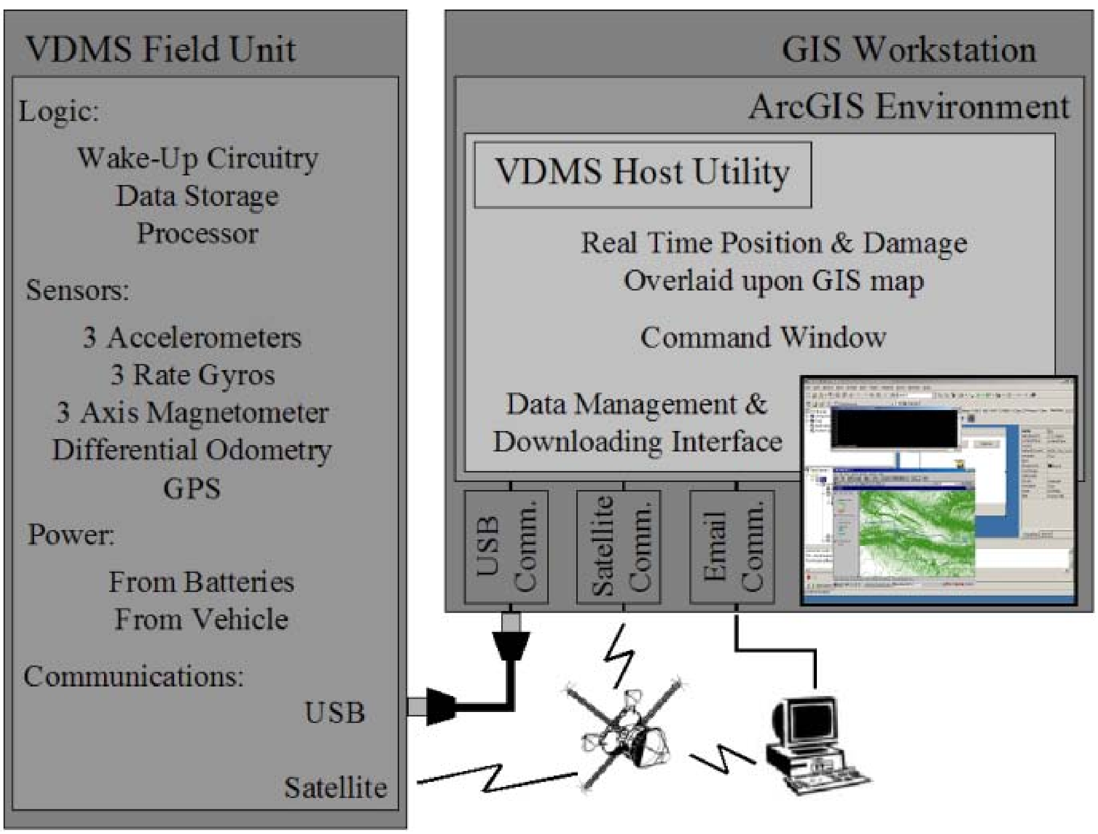


Figure 4. VDMTS hardware software configuration.

Figure 5. VDMTS Hardware. The photo on the left illustrates the hardware in the durable case The photos on the right illustrate the front and back panels of the VDMTS unit.

2.2.3 Vehicle-tracking data analysis routines

Analysis routines were developed to help users interpret the vehicle-tracking data. Analysis routines include: (1) identification of individual and unit tracking patterns, (2) identification of on and off-road use patterns, (3) identification of existing and emerging trail networks, (4) vegetation loss estimates, (5) identification and prioritization of LRAM sites and (6) development of data for carrying capacity models. The assessment of individual vehicle impacts and impact patterns is intended to address such management issues as:

1. How much damage does one type of vehicle cause relative to other vehicles if operated under similar conditions?
2. How much damage does a group of vehicles conducting a training exercise cause relative to other training events?
3. Do the spatial impact patterns for individual units and events differ from the historic patterns? Should we expect new areas to be impacted that have not historically been impacted?
4. How much time do vehicles spend in areas designed to minimize vehicle impacts like roads and staging areas? How much time is spent in critical habitat or near critical resources like cavity trees?
5. Where can we expect new trail networks to form?

Figure 6 shows individual vehicle and unit tracking patterns and off-road travel patterns. The inset map show potential trail networks. Figure 7 shows vegetation loss by management area and tabular summaries from the data.

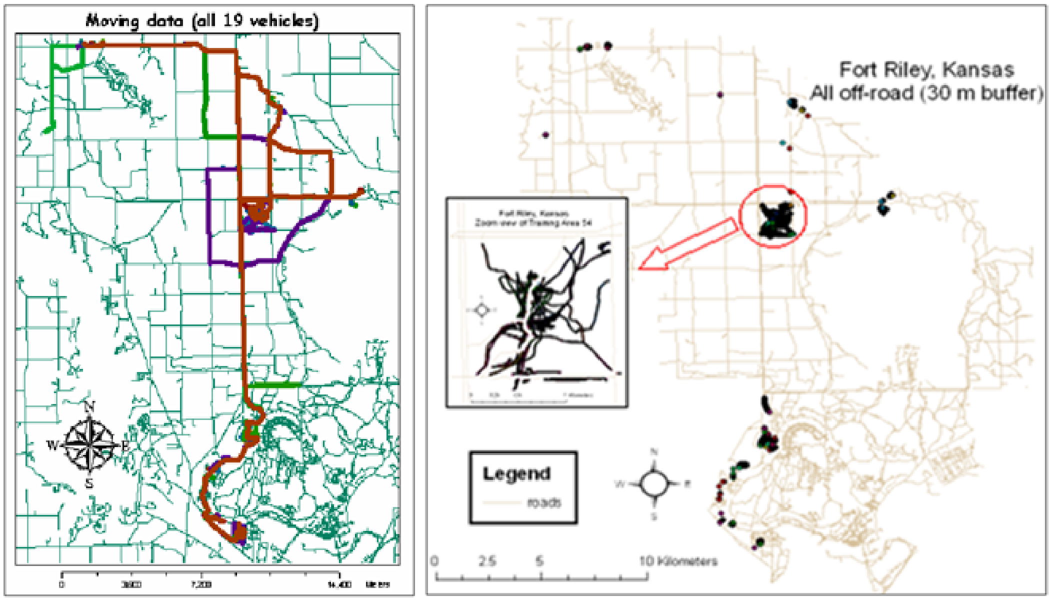
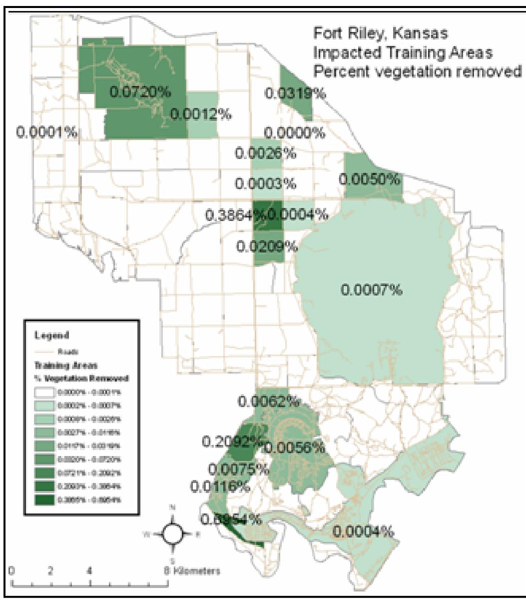


Figure 6. Summarized output from VDMTS tracking system on left shows individual vehicle travel patterns. Thin light green lines are installation road and trail network. Thick colored lines show vehicle travel. The map on right shows only off-road vehicle travel.



Vehicle Type	Dry Vegetation Loss (m^2)	Wet Vegetation Loss (m^2)	Increase (%)
M1A1	11,359	20,298	78.7
APC	3,164	5,688	79.8
HEMTT	4,121	7,245	75.8
HMMWV	1,801	2,188	21.5

Vehicle	Average Travel Distance (km)	Off-road Travel (km)	ATTACC ORF	Mean velocity (m/s)
M1A1	126.14	3.85	0.0282	6.33
M2A2	182.58	5.64	0.0297	6.74
M998	201.43	6.71	0.0320	6.70

Figure 7. Summarized output from VDMTS tracking systems. The map on left shows vegetation loss due to vehicle training summarized spatially as a percent of total vegetation and training area. The data at top right shows predicted vegetation loss under dry and wet conditions by vehicle type. The data at bottom right shows total distance traveled, off-road distance traveled, and average velocity by vehicle type. Results from this data can be used to predict dust emissions.

Methods were developed to identify areas with single and multiple tracking within an event (Wu et al. 2004, Rice et al. 2006). These analyses relate VDMTS data directly with multiple pass studies commonly found in the literature. Methods were developed to identify emerging trail networks (Wu et al. 2006, Wu et al. 2007). These methods use the number, direction, timing, and vehicle associated with each pass in an area to identify the potential for trails to develop.

The analysis was intended to identify emerging trails before severe impacts occur and proactive land management options are available. Management options may include blocking access to trails, providing alternative trails, or hardening trails. Methods exist to identify on and off-road travel and relevant impact assessment parameters (Ayers et al. 2005). Tabular summaries identify important model input data for other environmental models (Figure 7) (e.g., average velocity, soil type (from location data), vehicle type, and total mileage for input into dust models (Anderson et al. 2007a and b). Another example is percent off-road travel and average vegetation cover loss per mile for development of Army Training and Testing Area Carrying Capacity (ATTACC) Training Impact Factor (TIF) parameter development (Anderson et al. 2007a).

2.3 Advantages and limitations of the technology/ methodology

Table 2 lists and briefly describes alternative technologies or methodologies currently in place that at least partially meet the applicable need addressed by the VDMTS. Table 2 also summarizes advantages, limitations, and relative cost of the alternative technologies.

Table 2. Comparison of alternative technologies.

Technology	Description	Advantages	Limitations	Costs
Army Range Requirements Model (ARRM)	ARRM is a planning tool that models training throughput requirements for training and maneuver events for all Army installations. ARRM is used to derive the doctrinal requirements for training land, which form the basis for a variety of planning exercises.	Predicted training miles by unit and event. Available for all Army installations, units and training events. Data standardized for use with other data sources.	Training data only predicted at the installation level. No information on distribution in time or space. No site impact prediction. Does not account for changes in doctrine.	No costs for use in impact assessments since maintained by Army for other purposes. Only cost is interpretation of data. Costs not quantified.
Range Facility Management Support System (RFMSS)	RFMSS is a tool for scheduling and managing ranges and training areas.	Available for most Army and Marine installations. Provides near future planned and recent historical training land usage.	Training data only at training area level (no distribution within area). Metrics often in units difficult to relate to site impacts (e.g., training days). Data often not standardized for use with other data sources.	No costs for use in impact assessments since maintained by Army for other purposes. Costs often associated with data QA/QC and clean up. Cost to summarize data. Costs not quantified.
Range and Training Land Assessment (RTLA) program	Program to inventory and monitor installation natural resource condition. Often includes measure of land-use intensity.	Can provide temporally and spatially explicit patterns of training impacts when used with other data analysis methods. When combined with ARRM or RFMSS data, can relate mission with impact.	Not available at all installations. Data only available on annual or longer time interval. Training activity is cumulative impact with components not defined.	No costs for use in impact assessments if collected for other Army purposes. Annual data collection costs in \$100Ks. Data analysis for application typically costs \$10K-\$100K.
Installation Specific Vehicle Impact Studies	Experimental studies designed to quantify vehicle impacts. Frequently single to multiple passes of a specific vehicle.	Site-specific data of vehicle impacts on installation resources. Good for understanding processes involved in training impacts.	Data site-specific. Vehicle use often not representative of actual use. Difficult to extrapolate to actual unit/event impact. No spatial information on pattern of use.	Costs range from \$50K to > \$1M depending on data collected.

3 Performance Objectives

Table 3 lists the performance objectives and metrics. Performance metrics included qualitative and quantitative parameters. Quantitative parameter threshold values were based on information from previous studies. For example, thresholds for accuracy requirements for predicted DW, vegetation loss, and rut depth were based on: (1) variation typically seen in field measurements of the variable, (2) variation in predicted impacts associated with variations in input parameters, (3) limitation introduced from other sources of the model, hardware, or computations, (4) attempt to balance data collection costs and data quality, and (5) accuracy required to make management decisions. The metrics are based on data that were collected in the field. Performance metrics are organized by demonstration/validation study component and methodology component.

The following sections provide detailed descriptions and other information on each performance objective/metric including a summary of the relevance of each objective to the technology demonstration/validation. Note that reference to numbered metrics in this chapter correspond with the numbered metrics in Table 3.

3.1 Performance Objective 1: Accurate VDMTS hardware measurement for vehicle dynamic properties.

3.1.1 Metric 1.1: VDMTS hardware with inertial navigation system (INS) provides more accurate dynamic vehicle properties than GPS alone.

The objective of Metric 1.1 was to test the hardware component of the VDMTS. This metric tested the utility of having INS incorporated into the hardware to supplement the GPS location information. INS adds additional hardware cost, but provides improved dynamic vehicle properties in the absence of GPS signals or poor quality GPS signals. The test involved forcing conditions to lose GPS signal quality and forcing INS subsystem performance. Data requirements were simply performance of the INS subsystems with gain and loss of GPS signals. Evaluation of the INS subsystem performance was performed in the single live training event.

Table 3. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives — Demonstration Plan for Controlled Field Study and Live Training Single Event Study				
1. Accurate VDMTS hardware measurement of vehicle dynamic properties.	1.1. VDMTS hardware with INS provides more accurate dynamic vehicle properties than GPS alone	Vehicle position data without GPS signal	Ability to record in situations when GPS signals not available due to topography, vegetation, and related conditions.	Success Criterion Met: ▪ Hardware with INS improved dynamic property measurement.
	1.2. VDMTS hardware provides sufficient dynamic vehicle properties to predict vegetation loss and soil rutting.	Vehicle positional accuracy Vehicle turning radius accuracy Vehicle velocity accuracy	Vehicle positional accuracy within 5 m (16.4 ft) 95% of the time. Vehicle turning radius within 10 m (32.8 ft) 95% of the time. Vehicle velocity within 2.24 m/s (5 mph) 95% of the time.	Success Criteria Met: ▪ Position within 5 m 99.9% of recording time ▪ Average Positional Accuracy = 2.05 m. Success Criterion Met: ▪ TR within 10 m 95% of the time. Success Criteria Met: ▪ Velocity within 2.24 m/s 100% recording time ▪ Average Velocity error = -0.07 m/s.
2. Accurate VDMTS impact model predictions of site impacts under controlled condition	2.1. Correspondence between predicted and measured DW, vegetation loss and rut depth of site damage associated with individual vehicle use	Disturbed width Vegetation loss Rut depth	Correlation between predicted and measured DW > 0.8. Predicted DW within 20 cm of actual disturbed width for 95% of sample points. Correlation between predicted and measured vegetation loss > 0.7. Predicted vegetation loss within 20% of actual vegetation loss for 95% of sample points. Correlation between predicted and measured rut depth > 0.6. Predicted rut depths within 3 cm of actual rut depths for 95% of sample points.	Success Criterion Met: ▪ Correlation between predicted and measured DW = 0.89. Success Criterion Not Met: ▪ Predicted DW within 20 cm of actual disturbed width for 50% of sample points. Success Criterion Met: ▪ Correlation between predicted and measured vegetation loss > 0.9. Success Criterion Not Met: ▪ Predicted vegetation loss within 20% of actual vegetation loss for 86% of sample points. Success Criterion Not Met: ▪ Correlation between predicted and measured rut depth < 0.6. Success Criterion Not Met: ▪ Predicted rut depths within 3 cm of actual rut depths for 94% of sample points.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
3. Accurate VDMTS hardware measurement of vehicle static and dynamic properties.	3.1. VDMTS hardware provides sufficient static and dynamic vehicle properties to predict vegetation loss and soil rutting without GPS signal.	Vehicle positional accuracy	Vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal lost 90% of time.	Success Criteria Met: ▪ Vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal lost 100% of time ▪ Average GPS signal error 1.6 m (± 0.1 m) ▪ Average error between INS and GPS data 0.164±0.002 m.
4. Accurate VDMTS model predictions of site impacts during live training	4.1. Correspondence between predicted and measured DW, vegetation loss and rut depth of site damage associated with vehicle use.	DW Vegetation loss Rut depth	Predicted DW within 20 cm of actual disturbed width in 90% of the sample sites. Predicted vegetation loss within 20% of actual vegetation loss in 80% of the sample sites. Predicted rut depth within 4 cm of actual rut depth in 80% of the sample sites.	Success Criteria Not Met: ▪ Predicted DW within 20 cm of actual disturbed width in 45.6% of the sample sites ▪ Average error between predicted and measured data = 14.9 cm. Success Criteria Met: ▪ Predicted vegetation loss within 20% of actual vegetation loss in 95% of the sample sites ▪ Average error between predicted and measured vegetation loss =-1.8%. Success Criteria Met: ▪ Predicted rut depth within 4 cm of actual rut depth in 100% of the sample sites ▪ Average error between predicted and measured rut depth = 0.1 cm.
5. VDMTS Hardware durability	5.1. Reliable hardware use	Percent of recording time captured	Percent of recording time > 80% of military unit training time.	Success Criterion Met: ▪ 85.5% of military training time recorded.
Quantitative Performance Objectives - Demonstration Plan for Live Training Multiple Event Study				
6. VDMTS Hardware durability	6.1. Reliable hardware use	Percent of recording time captured	Percent of recording time > 80% of training time per vehicle type for any event	Success Criteria Met: ▪ 90.2% of total training time recorded ▪ ($p = 0.0002$) ▪ > 80% training time by vehicle recorded except for Heavy Expanded Mobility Tactical Truck (HEMTT).
7. Ease of system use	7.1. Ability of a technician-level individual to install and maintain hardware	Training time Hardware setup/take-down time	<4 hrs/Person <1 hr total/vehicle (Setup and take-down)	Success Criterion Met: ▪ 0.3hrs/Person ($p < 0.05$). Success Criterion Met: ▪ 0.19 hr/vehicle ($p < 0.05$).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
	7.2. Ability of a technician-level individual to retrieve and quality assurance/quality control (QA/QC) data	Training time QA/QC time	<4 hrs/Person <1 hr/vehicle data file	Success Criterion Met: ▪ 1.07 hrs/Person training time ($p < 0.05$). Success Criterion Met: ▪ 0.82 hr/vehicle data file QA/QC time ($p < 0.05$).
	7.3. Ability of a technician-level individual to summarize results	Training time Analysis time	<16 hrs/Person < 8 hr/Event Analysis	Success Criterion Met: ▪ 6.33 hrs/Person training time ($p < 0.05$). Success Criterion Met: ▪ 5.45 hr/Event Average Analysis time ($p < 0.05$).
8. Quality and accuracy of data for land-use decisions	8.1. Ability to use data for parameterization of models	Vehicle position DW Vegetation loss Time off-road	< 10 m position error < 20% error for time off-road, and impact severity	Success Criterion Met: ▪ 1.6 m position accuracy. Success Criterion Met: ▪ 6.3% error impact severity. Success Criterion Met: ▪ 1.0% error estimating time off-road.
	8.2. Ability to use data to identify training area use patterns	Vehicle positional accuracy Vegetation loss	<10 m position error for LRAM ID < 5 m position error for TES habitat analysis < 20% error in veg. loss	Success Criterion Met: ▪ 1.6 m position error for LRAM ID. Success Criterion Met: ▪ 1.6 m position error for TES habitat analysis. Success Criterion Met: ▪ 6.3% error estimating vegetation loss.
Qualitative Performance Objectives - Demonstration Plan for Live Training Multiple Event Study				
9. Ease of system use	9.1. Ability of a technician-level individual to install, remove, and review collected data	Questionnaire feedback from the technician on usability of hardware	Usable hardware system, QA/QC process, and analyses processes	Success Criterion Met: ▪ Usable hardware system, QA/QC process, and analyses processes.
10. Quality and accuracy of data for land-use decisions	10.1. Ability to use data for parameterization and identify training area use patterns	Questionnaire feedback from researchers on usability of system results	Usable analysis results	Success Criterion Met: ▪ Usable analysis results.

It was assumed that, if VDMTS hardware can meet these defined metrics, the system could sufficiently monitor vehicle dynamic properties to generate input parameter values for the impact models. Data were analyzed to compare cost to performance of alternative hardware.

3.1.2 Metric 1.2: VDMTS hardware provides sufficient dynamic vehicle properties to predict vegetation loss and soil rutting

The objective of Metric 1.2 was to test the hardware component of the VDMTS. The metric tested the VDMTS hardware's ability to measure vehicle dynamic properties (position, velocity, and turning radius). Vehicle position, velocity, and turning radius were selected because those are the input parameters required by the impact models. Success criteria for vehicle position, velocity, and turning radius were based on a considerations for hardware cost and impact model input requirements. Impact model inputs were based on sensitivity of the impact models to input parameters and relative effect of changes in output on model interpretations. Because these threshold values are somewhat subjective (based on research team's interpretation of data), field tests were conducted with reference systems (or study controls). Reference systems were a high-cost, high-precision GPS system and alternative low-cost, custom-made, vehicle-tracking systems consisting of only low-cost GPS units without INS. These controls bound the upper and lower limits of vehicle-tracking hardware with minimum and maximum cost alternatives.

It was assumed that, if the VDMTS hardware can meet these defined metrics, the system could sufficiently monitor vehicle dynamic properties to generate input parameter values for the impact models. Data were analyzed to compare cost to performance of alternative hardware.

3.2 Performance Objective 2: Accurate VDMTS impact model predictions of site impacts under controlled condition

3.2.1 Metric 2.1: Correspondence between predicted and measured DW, vegetation loss and rut depth of site damage associated with individual vehicle use

The objective of Metric 2.1 was to test the impact model component of the VDMTS. One metric was considered: the accuracy of the model to predict impacts for an expected range of vehicle static and dynamic properties.

Metric threshold values were set for each major impact model prediction (DW, vegetation loss, and rut depth). Threshold values for each of the three model outputs were defined in two ways. First, a correlation was found between actual and predicted values across the range of conditions tested. This metric is important to establish so that the model accurately captured the overall relationship between vehicle properties and site impact. A correlation greater than the specified threshold assured that the impact models accurately represented the relationship between vehicle dynamic properties and site impact across the complete range of potential vehicle-operating conditions.

Second, an overall output accuracy (i.e., predicted value was within a set value of the actual value for all sample data) was assessed. The majority of vehicle dynamic properties (velocity, turning radius) observed in actually training were often a subset of potential range of properties. For example, vehicles rarely traveled at high speeds while making sharp turns. An overall output accuracy across the range of values ensured the model predicted accurately for commonly occurring conditions. As an example, vegetation loss dramatically increases at a critical threshold turning radius. Predicting loss at this critical value is important to predicting overall cumulative impact and may not be well represented in an overall correlation.

Metrics were tested with controlled field studies including vehicle static properties (vehicle weight, etc), vehicle dynamic properties (turning radius, velocity), multiple passes, and different site conditions. Two main tests were performed: alpha and beta tests. The alpha test tested the models in a region included in the original model development (Fort Riley). The beta test tested the models in regions not included in original model development (Eglin Air Force Base [AFB,] and Pohakuloa Training Area). The alpha test tested the models at Fort Riley, a location included in the original model development. As such, the general site conditions were similar including native prairie grassland vegetation and similar soils. However, site conditions of the alpha test varied from the conditions used in the original test.

The alpha test also included four different vehicle types (two-wheeled, two-tracked). The alpha test included multiple tracking that was not included in the earlier Fort Riley study. The beta test tested the models at Eglin AFB and Pohakuloa Training Area, locations not included in the

original model development. As such, the general site conditions were different including vegetation types and soils not previously included in model development. The beta test included some vehicles types different from those previously tested. The beta test included multiple tracking that was not included in the earlier model development datasets. The beta test included three different vehicle types.

It was assumed that, if the VDMTS impact models can meet these defined metrics, the models were sufficient to predict site impacts during live training for the range of vehicles types and training doctrine likely to be encountered in the field.

3.3 Performance Objective 3: Accurate VDMTS hardware measurement of vehicle static and dynamic properties

3.3.1 Metric 3.1: VDMTS hardware provides sufficient static and dynamic vehicle properties to predict vegetation loss and soil rutting without GPS signal

The objective of Metric 3.1 was to test the hardware component. Specifically the test evaluated the utility of the INS system in the live training event. The metrics were tested with data from tracking of a live field training event. The performance of the INS was dependent on what the vehicle is doing (e.g., traveling fast or slow, making sharp or gradual turns, traveling on rough to smooth terrain, etc.). Data were obtained from a live event that captures actual vehicle use patterns. Tracking systems stored both GPS and INS signals separately resulting in three data sets: (1) GPS only, (2) INS only, and (3) Geographic Positioning and Inertial Navigation System (GPS/INS) combined signals. These three datasets allowed researchers to identify any point during the training event and evaluate GPS signal loss starting at that time. From that start point, location, turning radius and velocity were calculated for each dataset for a period into the future until the evaluation metric is exceeded for the INS-only dataset. A systematic sampling was made from the complete tracking event to identify simulated GPS signal loss times.

The evaluation criteria evaluated the positional accuracy when GPS signal was unavailable. It was assumed that if, the VDMTS passed this test, then the INS hardware provided additional value over GPS only hardware.

3.4 Performance Objective 4: Accurate VDMTS model predictions of site impacts during live training

3.4.1 Metric 4.1: Correspondence between predicted and measured DW, vegetation loss and rut depth of site damage associated with vehicle use

The objective of Metric 4.1 was to test the combination of the hardware and impact model components. One metric was considered: the accuracy of the model in predicting impacts for actual vehicle use during live training. Threshold values were set for each major impact model prediction (DW, vegetation loss, and rut depth). Threshold values for each of the three model outputs were defined. An overall output precision (i.e., with a specified amount of the actual value) for a specified percentage of all impact areas was assessed. These values reflected the same level of accuracy defined for previous objectives. However, the percentage of impact points correctly predicted was lower. This lower percentage was because of additional uncertainty about site condition like soil type, soil moisture, and vegetation.

Metrics were tested through the tracking of a live field training event at three test sites. Vehicles of different types and expected use patterns were selected through consultation with installation representatives. Vehicles were tracked for approximately 1 week. Researchers randomly selected predicted impact points, located those points in field, and measured actual impacts. Comparison of predicted and actual impacts determined system performance. The first site was a grassland installation (Fort Riley) with significant off-road travel, but with limited signal interference expected. The second site was a forested installation (Fort Benning) with extensive road/trail travel and greater signal interference expected. In the single live training events, 38 vehicles were tracked across the two installations.

It was assumed that, if the VDMTS hardware and impact models met these defined metrics, they were sufficient to predict site impacts during live training.

3.5 Performance Objective 5: VDMTS hardware durability during live training single event study

3.5.1 Metric 5.1: Reliable hardware use

The objective of Metric 5.1 was to evaluate hardware performance and durability during a single live training event. One metric was considered: the percent of total data collected. In other words, the percent of total data lost due to any hardware failure including loss of unit, loss of power, or failure of any hardware component.

It was assumed that, if VDMTS hardware met this defined metric, it was sufficiently durable to track multiple events reliably.

The metric was tested using tracking of a live field training event at three tests sites. Vehicles of different types and expected use patterns were selected in consultation with installation representatives. The first site, a grassland installation (Fort Riley), has significant off-road travel, but has limited signal interference expected. The second site, a forested installation (Fort Benning), has extensive road/trail travel and greater signal interference expected. The third site, Pohakuloa Training Area, had little developed networks so it was anticipated that off-road training would occur. This also allowed the opportunity to test the models under conditions outside of those where they were developed. Vehicles were tracked for approximately 1 week. Actual usable data were compared with potential data to determine metric success. Total available data were determined based on study start time, study end time, and data collection rate. In this phase of the study 2254.8 hours of data were collected out of a total training time of 2637.6 hours.

3.6 Performance Objective 6: VDMTS hardware durability during live training multiple event study

3.6.1 Metric 6.1: Reliable hardware use

The objective of Metric 6.1 was to evaluate hardware performance and durability of the VDMTS system to collect data during live training events. One metric was considered: the percent of total data for each vehicle type collected (i.e., the percent of total data for each vehicle type not lost due to any hardware failure including loss of unit, loss of power, or failure of any

hardware component to function properly). The metric was tested using tracking of multiple live field training events. Vehicles of different types and expected use patterns were selected in consultation with installation representatives. Vehicles were tracked for approximately 1 week. Actual usable data were compared with total potential data to determine metric success. Total available data were determined based on study start time, study end time, and data collection rate. Data were summarized by vehicle, event, installation and overall performance. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events (136 vehicles across nine vehicle types). were tracked (Appendix B includes a comprehensive table of vehicles tracked by date and location.) Percent recording time criteria success was evaluated using a one-sided T-test to test the hypothesis that VDMTS hardware recording time statistically exceeded the success criteria. A total of 13587.1 hours out of 15056.8 possible training hours were recorded.

It was assumed that, if the VDMTS hardware met this defined metric, it was sufficiently durable to track multiple events reliably.

3.7 Performance Objective 7: Ease of system use

3.7.1 Metric 7.1: Ability of a technician-level individual to install and maintain hardware

The objective of Metric 7.1 was to determine the effort required to train a technician to properly instrument a vehicle and to instrument vehicles for tracking events. Two metrics were considered: time to train the technician and time to instrument a vehicle. The metrics were tested by training one or more technicians at each installation (Fort Riley, Fort Benning, and Pohakuloa Training Area) in use of VDMTS hardware and vehicle mounting. Training times were recorded. Live training events were identified for tracking in coordination with the installation. Installation technicians mounted VDMTS systems. Mounting times were recorded for each event. After the training event, installation technicians removed VDMTS hardware. Removal types for each event were recorded. Actual training time and combined VDMTS mounting/dismounting times were compared with the success criteria. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events were tracked (136 vehicles across nine vehicle types).. Mounting/dismounting criteria success was

evaluated using a one-sided T-test to test the hypothesis that vehicle set-up/take-down times were statistically less than the success criteria.

It was assumed that, if the VDMTS system met this defined metric, it was sufficiently easy to setup and take-down.

3.7.2 Metric 7.2: Ability of a technician-level individual to retrieve and QA/QC data

The objective of Metric 7.2 was to determine the effort required to train a technician to check the quality of data obtained from VDMTS hardware mounted on vehicles during live training events. Two metrics were considered: time to train the technician and time to check data quality. The metrics were tested by training one or more technicians at each installation (Fort Riley, Fort Benning, and Pohakuloa Training Area) to check the quality of data from VDMTS hardware units that were mounted on military vehicles. Training times were recorded. Live training events were identified for tracking in coordination with the installation. VDMTS systems were mounted on training vehicles.

After the training event, VDMTS hardware was removed from the vehicles. Installation level technicians downloaded the VDMTS data and performed QA/QC data checks. QA/QC data checks consisted of opening the vehicle-tracking file (.vdm file) on a computer to verify completeness, ensure that correct vehicle information and training mission were recorded, confirm that the file was in proper format and not corrupted, and confirm that adequate vehicle positional accuracy had been obtained. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events were tracked (136 vehicles across nine vehicle types). (Appendix B includes a comprehensive table of vehicles tracked by date and location.) Actual QA/QC times and QA/QC success criteria were compared. QA/QC criteria success was evaluated using a one-sided T-test to test the hypothesis that QA/QC times are statistically less than the criteria.

It was assumed that, if the VDMTS system met this defined metric, the data QA/QC process was sufficiently easy for installation use.

3.7.3 Metric 7.3: Ability of a technician-level individual to summarize results

The objective of Metric 7.3 was to determine the effort required to train a technician to analyze VDMTS data and to analyze data obtained from VDMTS hardware mounted on vehicles during live training events. Two metrics were considered: time to train the technician and time to analyze the data. The metrics were tested by training one or more technicians at each installation (Fort Riley, Fort Benning, and Pohakuloa Training Area) to conduct routine data analyses. Live training events were identified for tracking in coordination with the installation. VDMTS systems were mounted on training vehicles. After the training event, VDMTS hardware was removed from the vehicles. Installation level technicians analyzed VDMTS data and summarized results. The amount of time to train the technician and the amount to time the technician required to conduct each analysis were recorded. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events were tracked (136 vehicles across nine vehicle types). (Appendix B includes a comprehensive table of vehicles tracked by date and location.) Actual analysis and VDMTS analysis were compared with the success criteria. Analysis criteria success was evaluated using a one-sided T-test to test the hypothesis that analysis times were statistically less than the criteria.

It was assumed that, if the VDMTS system met this defined metric, the data analysis process was sufficiently easy for installation use.

3.8 Performance Objective 8: Quality and accuracy of data for land-use decisions

3.8.1 Metric 8.1: Ability to use data for parameterization of models

The objective of this metric was to determine if the data quality was sufficient for use as inputs in models (e.g., Fort Riley nLS model, ATTACC) used in land-use decision making (Bussen 2009, Sullivan et al. 1997, Sullivan and Anderson 2000). Data accuracy refers to the closeness of the data to its true values. In this demonstration, DW, vegetation loss, and impact severity data and their associated accuracies were predicted based on the models previously validated in the first demonstration phase (Section 5.2, p 49). However, the accuracy of these predictions depends on the accuracy of the vehicle positional data. The VDMTS system analyzed the accuracy of

each data point based on satellite reception and differential correction. Previously demonstrated accuracy was combined with measured vehicle positional accuracy to determine applicability of system for different land-use decisions under this demonstration. The resolution of each specific model defined the acceptable accuracy of data for model parameterization. If accuracy was greater than the model resolution, the data quality was sufficient for model parameterization. Model resolution and input requirements were obtained from literature and individuals researching model implementation and development on installations.

Depending on the model, different data types are required. Vehicle position was required to accurately predict DW and vegetation removal. These data allow for more accurate parameterization of a Kinematic Wave model used at Fort Riley to predict erosion and gully formation. Currently, the model uses land-use/landcover data to predict the surface roughness (i.e., Manning's n) from a lookup table (Bussen 2009). The spatial resolution of this land-use/landcover dataset is 30 m. Vegetation removal data acquired following a training event could be combined with the land-use/landcover dataset resulting in more accurate surface roughness estimations (e.g., an area under heavy training with high vegetation loss might be considered bare instead of the mixed prairie determination from the land-use/landcover data). The model uses 10 m resolution elevation data. Therefore, the vehicle positional accuracy must be ≤10 m. If 3 m positional accuracy is obtained, 3 m resolution elevation data could be used for the model producing results that are even more reliable.

The VDMTS calculated percent time off-road, vegetation loss, and impact severity allow for better estimates of the Vehicle Off-Road Factor, Vehicle Severity Factor, and Vehicle Conversion Factor for the ATTACC methodology. Sullivan and Anderson (2000) described a methodology for estimating ATTACC parameters that compared the existing method with subject matter experts assigned factors. The average error between these two methods was approximately 20%. Therefore, the success criteria established for time off-road, vegetation loss, and impact severity was an error ≤20%. Errors ≤20% result in values that are more accurate than previously used. The error was calculated by combining validated model accuracy with observed VDMTS positional accuracy demonstrated.

The metrics were tested by performing routine data analysis following training events. Live training events were identified for tracking in coordination with the installation. VDMTS systems were mounted on training vehicles. After the training event, VDMTS hardware was removed from the vehicles. VDMTS data were processed through the models and the results summarized. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events were tracked (136 vehicles across nine vehicle types). (Appendix B includes a comprehensive table of vehicles tracked by date and location.) VDMTS live training data combined with accuracy demonstrated were compared to input resolution thresholds established for the Fort Riley nLS model and ATTACC methodology.

It was assumed that, if the VDMTS system met this defined metric, the data quality was sufficient for parameterization of models.

3.8.2 Metric 8.2: Ability to use data to identify training area use patterns

The objective of this metric was to determine if the data quality was sufficient to identify training area use patterns. Identifying training area use patterns assists installation land managers in identifying: LRAM sites, low water crossing usage, emerging trails, and impact to TES habitats (e.g., Red-cockaded Woodpecker [RCW] and Gopher Tortoise). As described for Metric 3.1, vegetation loss used in this demonstration was calculated using the theoretical impact models. Previously demonstrated positional accuracy combined with positional accuracy from this study was compared with data requirements to determine applicability of system for different land-use decisions.

Vehicle positional accuracy is required for all training use pattern identification. Some pattern identification (e.g., LRAM site identification) require vegetation loss predictions (from previously validated models). Current methods of LRAM site identification require feedback from units after training events and accuracy is lacking. Consultation with Fort Riley land managers established a vegetation loss accuracy requirement of ≤20% for LRAM site identification. Identifying low water crossing usage and emerging trails allows resources to be focused on regions with higher usage intensity. Fort Riley ITAM personnel also expressed an interest in combining VDMTS obtained vehicle positional data with available National Geospatial Intelligence Agency (NGA) multispectral and panchromatic

satellite images to help extrapolate installation wide training impacts. The resolution of these images is 0.5 – 2.5 m. Fort Riley GIS technicians established a vehicle positional accuracy requirement of ≤10 m. This use of VDMTS data is applicable across all installations as these satellite images can be obtained anywhere in the continental United States.

The knowledge of vehicle movement relative to known RCW cavity trees and Gopher Tortoise burrows is desired for proper management of these species on installations. VDMTS data allows determination of adherence to RCW cavity tree avoidance guidelines. Vehicle positional data can be analyzed with respect to RCW behavioral responses (e.g., flushing or feeding). The probability distribution of the vehicle location and location of sensitive habitats allows a determination of negative impacts per distance traveled. Through consultation with US Fish and Wildlife, a vehicle positional accuracy requirement of ≤5 m was established for assessing TES habitat impacts.

The metric was tested by performing routine data analyses following training events. Live training events were identified for tracking in coordination with the installation to best address the training use patterns desired. VDMTS systems were mounted on training vehicles. After the training event, VDMTS hardware was removed from the vehicles. VDMTS data were analyzed and results summarized. Events were tracked at Fort Riley, Fort Benning, and Pohakuloa Training Area. A total of 14 events were tracked (136 vehicles across nine vehicle types). (Appendix B includes a comprehensive table of vehicles tracked by date and location.) Results were evaluated to test the hypothesis that vehicle positional accuracy demonstrated was statistically within the success criteria established.

It was assumed that, if the VDMTS system met this defined metric, the data were accurate enough to identify training area use patterns.

3.9 Performance Objective 9 (qualitative): Ease of system use

3.9.1 Metric 9.1: Ability of a technician-level individual to install, remove, and review collected data

The objective of this metric was to determine the effort required to train a technician in VDMTS operation and actually perform tracking events and data analyses. To assess this qualitative metric, feedback was obtained from

the trained technician on the utility and sufficiency of the training and VDMTS process in the form of a questionnaire and evaluation form. The metric was tested by training one or more technicians at each installation (Fort Riley, Fort Benning, and Pohakuloa Training Area) in use of VDMTS process. Live training events were identified for tracking in coordination with the installation. Installation level technicians performed all steps of the VDMTS process (installation and use of VDMTS hardware, QA/QC of data, and VDMTS data summary). A total of 14 events were tracked.

An evaluation form was given to technicians to qualitatively and quantitatively assess ease of system use and ability to make land-use decisions based on process results (Appendix D). Technicians only filled in the evaluation sections relating to their experience with the system. One section allowed the user to give a 1-10 ranking for each of the steps in the VDMTS data collection, QA/QC, and analysis processes. A ranking of 10 indicated no issues with that step while a ranking of 1 indicated an unusable/difficult step. Comments on each step were also requested. A set of general questions were asked. Six installation technicians were given the evaluation following their training and use of the system. Since this was a small sample, four additional students from the University of Illinois and University of Tennessee, Knoxville were trained and asked to evaluate the system and training. The students were of B.S. and M.S. backgrounds in similar fields of study as military installation technicians.

It was assumed that an average ranking >7 indicated no issues with that particular step in the VDMTS process.

3.10 Performance Objective 10 (qualitative): Quality and accuracy of data for land-use decisions

3.10.1 Metric 10.1: Ability to use data for parameterization and identify training area use patterns

The objective of this metric was to determine if the data quality was sufficient use as inputs in various predictive models and to identify training area use patterns. Land manager and researcher feedback was required to determine if VDMTS obtained datasets were actionable information. The metric was tested by training one or more technicians at each installation (Fort Riley, Fort Benning, and Pohakuloa Training Area) to analyze VDMTS data and summarize them into useable forms. Live training events

were identified for tracking in coordination with the installation. Installation level technicians performed all steps of the VDMTS process (data processing, analysis, and summary).

Technicians were given an evaluation form to qualitatively and quantitatively assess ease of system use and ability to make land-use decisions based on process results (Appendix D). Technicians only filled in the evaluation sections relating to their experience with the system. One section allowed the user to give a 1-10 ranking for each of the steps in the VDMTS data collection, QA/QC, and analysis processes. A ranking of 10 indicated no issues with that step while a ranking of 1 indicated an unusable/difficult step. Comments on each step were also requested. A set of general questions were asked. Six installation technicians were given the evaluation following their training and use of the system. Since this is a small sample, four additional students from the University of Illinois and University of Tennessee were trained and asked to evaluate the system and training. The students were of B.S. and M.S. backgrounds in similar fields of study as military installation technicians. It was assumed that an average ranking >7 indicated no issues with that particular step in the VDMTS process.

4 Site Description

This chapter provides a short description of the selected demonstration sites. The two main demonstration sites were Fort Riley, KS and Fort Benning, GA. Additional studies were performed at Eglin AFB, FL and Pohakuloa Training Area, HI.

4.1 Site selection

For this study, Fort Riley was considered the alpha test site. Fort Riley data were used in original impact model development and concept development. As such, use of impact models at this location provided a test of the models/technology within the model development parameters. Fort Riley also represents a less stressing environment in that it is relatively flat open grasslands with little GPS signal interference.

Fort Benning was considered the beta test site. No data from Fort Benning were used in the development of the model. As such, this demonstration site represents an evaluation of the models/technology outside the original bounds of model development. Fort Benning's topography and vegetation are more diverse allowing for a more robust evaluation of the VDMTS GPS/INS tracking capabilities. Fort Benning was included to allow use of model/technology output with other SERDP/ESTCP investments.

Eglin AFB was chosen as an alternative site for Fort Benning for the controlled vehicle impact test since the cost to perform the study at Fort Benning was prohibitive. Eglin AFB was selected as an alternative site for its similar soil and vegetation conditions.

Installation land managers at Pohakuloa Training Area expressed interest in using the VDMTS system to identify vehicle impacts in the newly opened Keamuku Training Area. This location allowed the system to be tested and validated under different conditions and on different vehicle types.

The combination of the four sites provides a broad range of site characteristics (topography, soil, and vegetation), vehicle types, and training doctrine.

4.2 Site location, history, and site characteristics

4.2.1 Fort Riley, KS

Fort Riley, which is located in northeastern Kansas (Figure 8), has an area of 41,154 ha. It is located in the Bluestem Prairie region, is characterized by rolling plains, and is dissected by stream valleys. Installation lands are a mix of native prairie and introduced vegetation. Fort Riley is located within a 1.6 million ha region in eastern Kansas containing the largest untilled tallgrass prairie landscape in the world (Knapp and Seastedt 1998). Tall grasses dominate this area and wood and shrub lands occur mainly in the stream valleys (Althoff and Thien 2005). There are three major vegetation communities on Fort Riley: grasslands (ca. 32,200 ha), shrublands (ca. 1600 ha), and woodlands (ca. 6000 ha). Grasslands are dominated by big bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), and little bluestem (*Schizachyrium scoparium*) with other grasses and forbs occurring in lesser abundance. Shrublands are dominated by buckbrush (*Symphoricarpos orbiculatas*), smooth sumac (*Rhus glabra*), and rough-leaved dogwood (*Cornus drummondii*) with a mixture of grasses and forbs. Shrublands occur along woodland edges and in isolated patches in grassland areas.

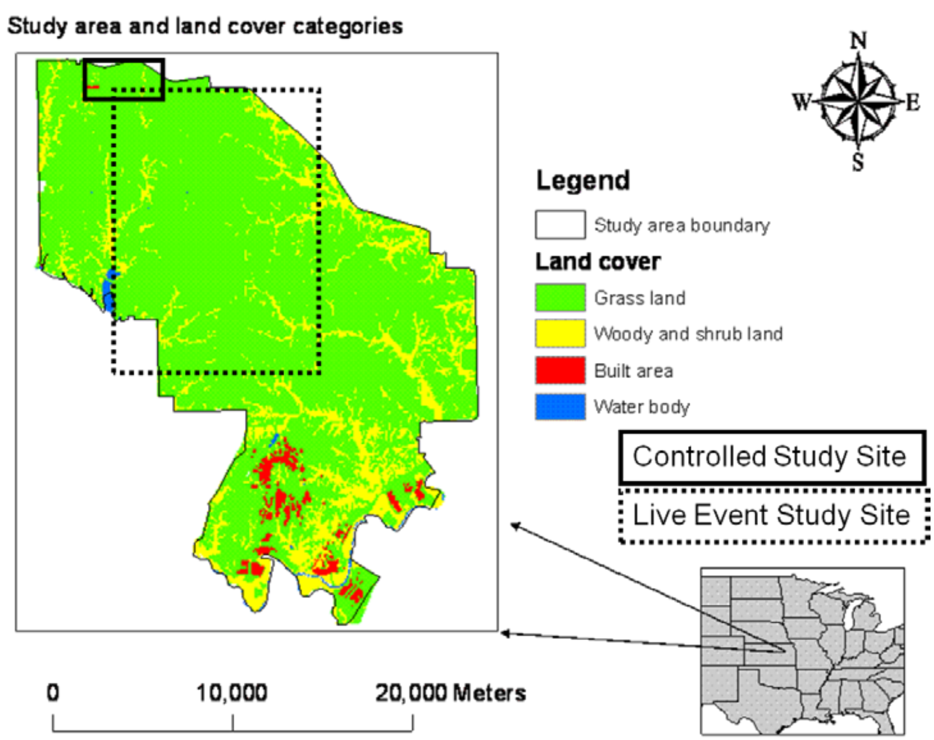


Figure 8. Fort Riley controlled field study and live training event study locations.

Woodlands typically occur along riparian lowlands and are characterized by chinquapin oak (*Quercus muhlenbergii*), bur oak (*Quercus macrocarpa*), American elm (*Ulmus americana*), hackberry (*Celtis occidentalis*), and black walnut (*Juglans nigra*).

Since the early 1940s, a variety of military training activities including field maneuvers, combat vehicle operations, mortar and artillery fire, and small-arms fire have taken place at Fort Riley. These activities have affected the ecosystem processes, including disturbing ground and vegetation cover; increasing soil erosion; changing plant composition, vegetation structures, habitats, and biodiversity; and landscape fragmentation.

The majority of mechanized maneuver activities has occurred on the northern 75% portion of Fort Riley (17 of the 18 designated training areas ranging from 577-3,024 ha) for the past 4 decades. Typical maneuvers by large tracked and wheeled vehicles that traverse thousands of hectares in a single training exercise can cause impacts ranging from minor soil compaction and lodging of standing vegetation to severe compaction and complete loss of vegetative cover in areas with concentrated training use. Wildfires resulting from training activities may occur during any season on the installation.

Figure 8 shows the study areas at Fort Riley. The controlled field study site location was selected to allow the study access to installation representative soil and vegetation types without conflicting with ongoing training activities. The live training event study site location identifies the region most commonly used by maneuver training events.

4.2.2 Fort Benning, GA

Fort Benning, which is located in southwest Georgia (Figure 9), is 73,503 ha in size. Most of the installation lies in west central Georgia, but a small part extends into Russell County, AL. Long, hot summers and mild winters characterize the region’s climate. Average annual precipitation is approximately 740 mm with a monthly average of about 62 mm. Most of the precipitation occurs in the form of spring and summer thunderstorms. Heavy rains are typical during the summer, but can occur in any month. Snow accounts for less than 1% of the annual precipitation.

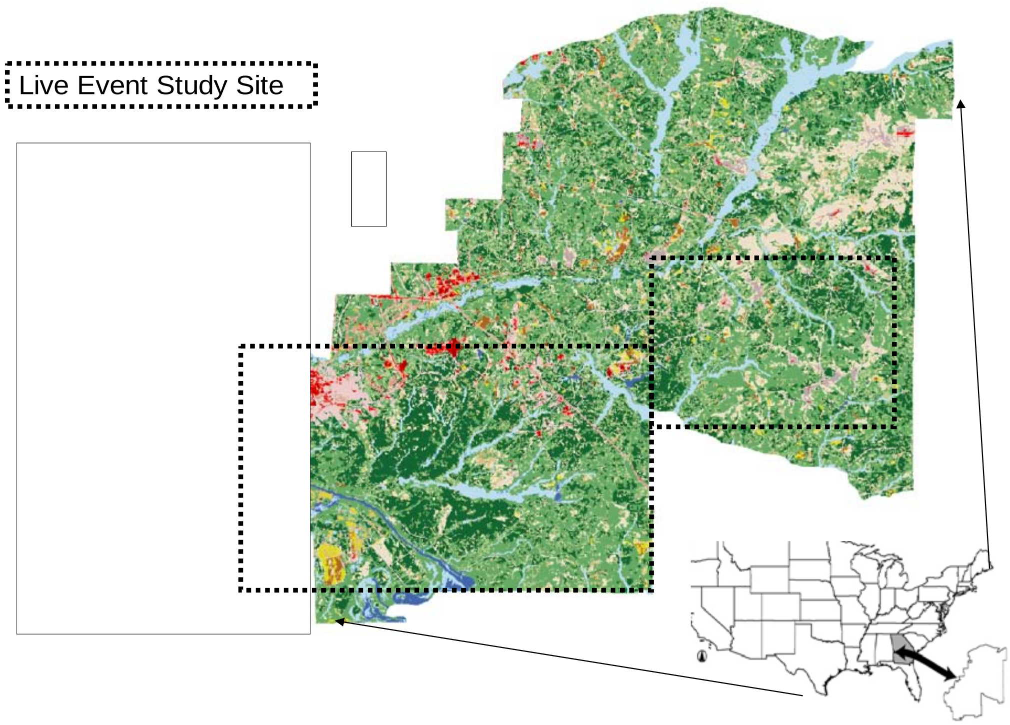


Figure 9. Fort Benning controlled field study and live training study locations.

The installation is situated on the Fall Line transition zone, which is the geographic area between the Southern Appalachian Piedmont and the Coastal Plain. Soils are composed of clay beds, weathered Coastal Plain material, and alluvial deposits from the Piedmont (Knowles and Davo 1997). Fort Benning is classified as a southeastern Mixed Forest Province of the Subtropical Division (Bailey 1995). This region is characterized by second growth pine forests of longleaf (*Pinus palustris*), loblolly (*Pinus taeda*), and slash pines *(Pinus elliotii*). Patchy land cover forming a mosaic of open or forested areas characterizes the installation.

Open areas are used for military training or managed for wildlife openings. The military open areas are frequently clear-cut parcels of land dominated by grass and bare soil. Since the early 1920s, land impacts due to light and heavy military activities (e.g., infantry, artillery, wheeled, and tracked vehicle training) frequently occur in open areas. Because of the Base Realignment and Closure Commission (BRAC), the US Army Armor Center and School is currently being relocated to Fort Benning. This realignment will result in heavier military training than has historically occurred on the installation, especially in the southern Good Hope Maneuver Area.

Figure 9 shows the study areas at Fort Benning. The live training event study site location identifies two regions most commonly used by maneuver training events. One location is of primary interest to the ITAM community (southwest area) due to erosion issues. One location is of primary interest to the conservation community (northeast area) due to potential training conflicts with RCW habitat.

4.2.3 Eglin AFB, FL

Eglin AFB is located on the Florida panhandle (Figure 10). Due to prohibitive costs at Fort Benning, Eglin AFB was selected for the controlled study for this demonstration under ESTCP guidance. It is the largest forested military reservation in the United States consisting of 187,995 ha within Santa Rosa, Okaloosa, and Walton counties (US Air Force 2010). Eglin AFB has a subtropical climate characterized by humid warm summers and mild winters. However, the northern portion of the base has more of a continental climate than subtropical as its distance from the Gulf reduces the moderating effect. A majority of the soils on Eglin AFB belong to the Lakeland Association with Lakeland Sand the dominate soil type. Doravan mucks are in the Lakeland Association and are the second most abundant soil on Eglin AFB. Eglin's sandhills are comprised of old growth longleaf pine forests with grasses, forbs and low stature shrub groundcover. This structure is maintained by frequent fires (3-5 year frequency). Eglin AFB is the largest and least fragmented single longleaf pine ownership in the world.

4.2.4 Pohakuloa Training Area, HI

Pohakuloa Training Area (PTA) is located on the island of Hawaii (

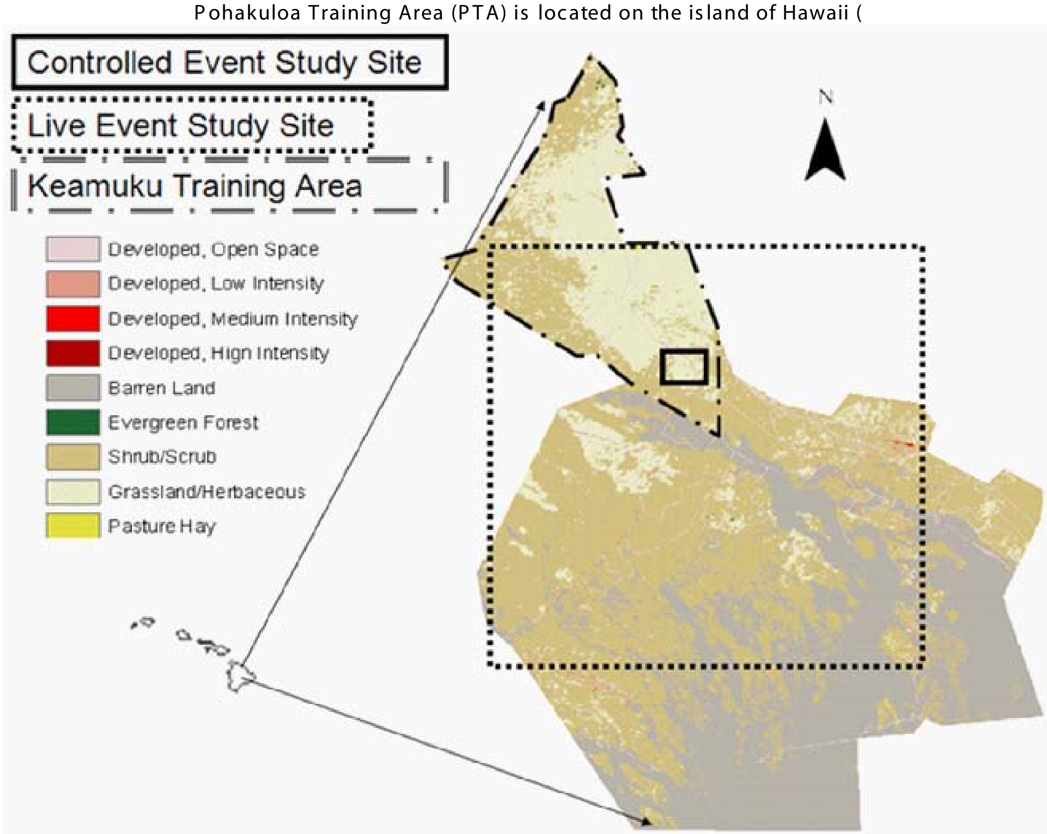


Figure 11). It is 53,735 ha in size making it the largest Army training area in Hawaii (US Army Environmental Command 2008). The installation is located in the saddle between Mauna Loa and Mauna Kea volcanoes. The climate at PTA is classified as cool and tropical with an annual mean temperature ranging from 10-16 °C depending on the elevation (US Department of the Army 2002). Diurnal temperature fluctuations are greater than seasonal variations. The mean annual precipitation ranges from 10-41 cm across the installation with the highest monthly precipitation occurring in the winter months. PTA is located in the Hawaiian Islands Province of the Rainforest Division (Bailey 1995). Soils on PTA are thin and poorly developed. The predominant soil types are Keekee loamy sand and Kilohana loamy fine sand, formed in volcanic ash, sand, and cinders.

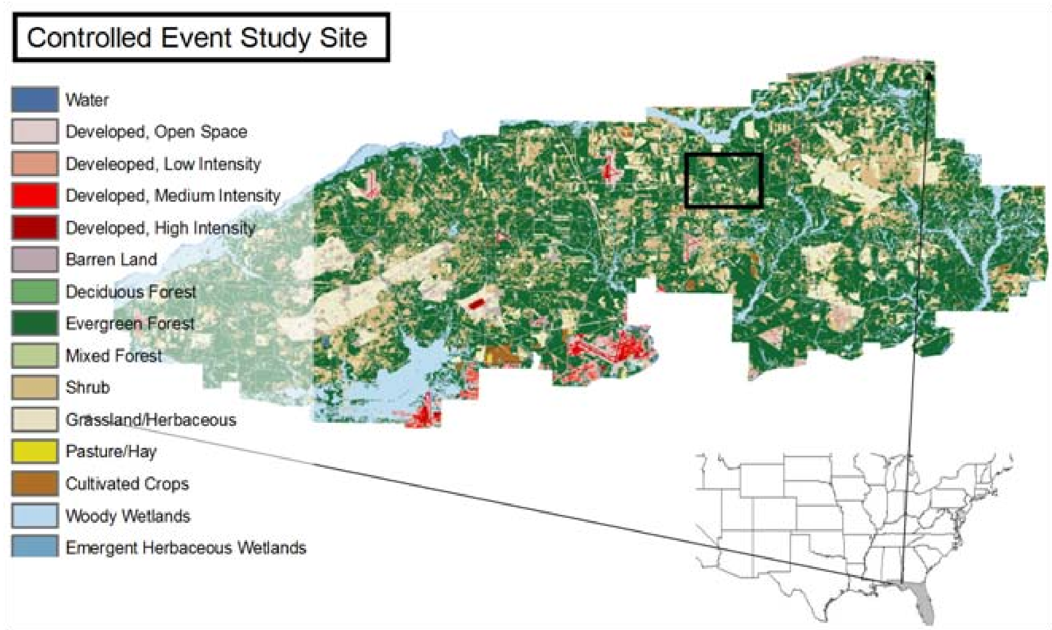


Figure 10. Eglin AFB controlled field study location.

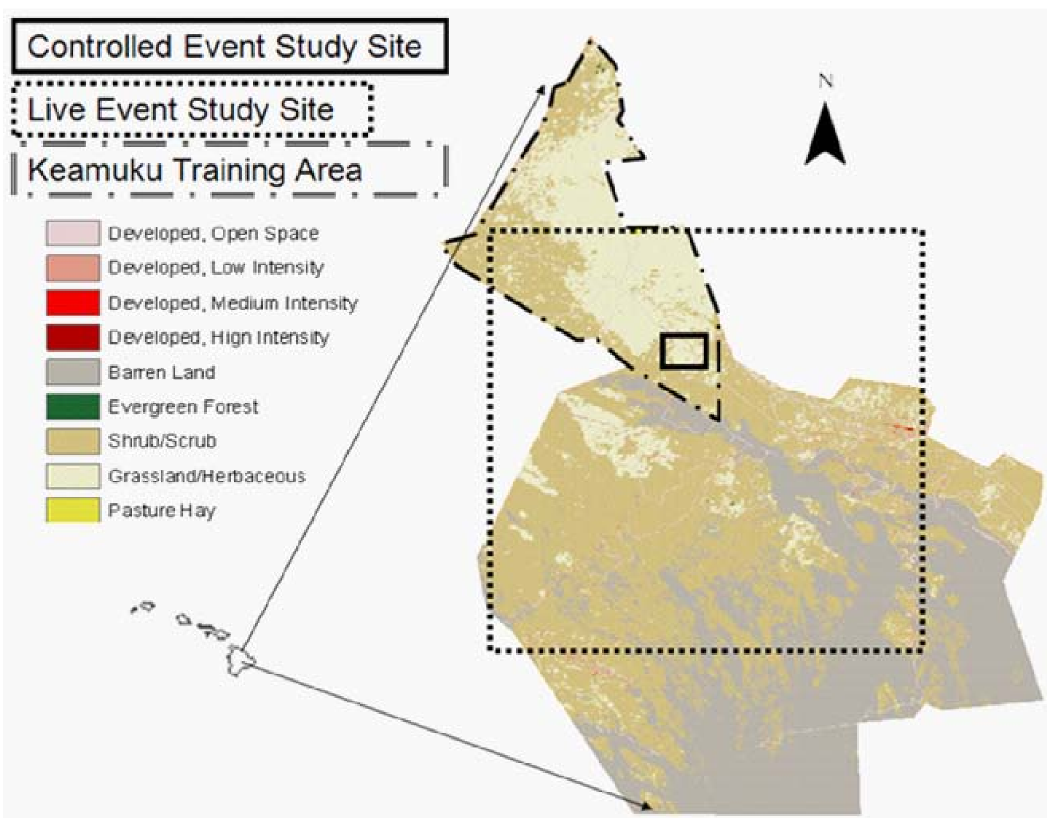


Figure 11. PTA controlled field study and live training event study locations.

Recent lava flows cover approximately 80% of the surface. Vegetative cover is largely a function of the age of the lava flow on which it grows and varies tremendously. Lichens (e.g., *Stereocoulon vulcani*) and ferns (e.g., *Pella trenifolia*) are generally early colonizers of lava flows. Additionally, grassland, shrubland, and treeland make up the vegetation communities at PTA. Grassland is composed of native grasses (e.g., *Eragrostis atropioides, Trisetum glomeratum, and Panicum tenuifolium*) and invasive fountain grass (*Pennisetum setaceum*). Shrubland is dominated by *Dodonaea viscosa* and *Myoporum sandwicense* with forb and grass understory species. Treeland vegetative communities are characterized by a *Metrosideros polymorpha* dominated overstory with a *Dodonaea viscosa* and *Styphelia tameiameiae* shrub understory.

PTA is used for maneuver unit live fire, maneuver training, and artillery live fire (US Department of the Army 2002). Approximately 12,950 ha are suitable for maneuver training. It is the only training area in Hawaii capable of supporting coordinated live firing from assigned crew-served vehicles of the infantry and artillery in conjunction with live air support. In 2006, the 9210 ha Keamuku Training Area was added to PTA to support battalion maneuver training and to support training of the Stryker Brigade Combat Teams.

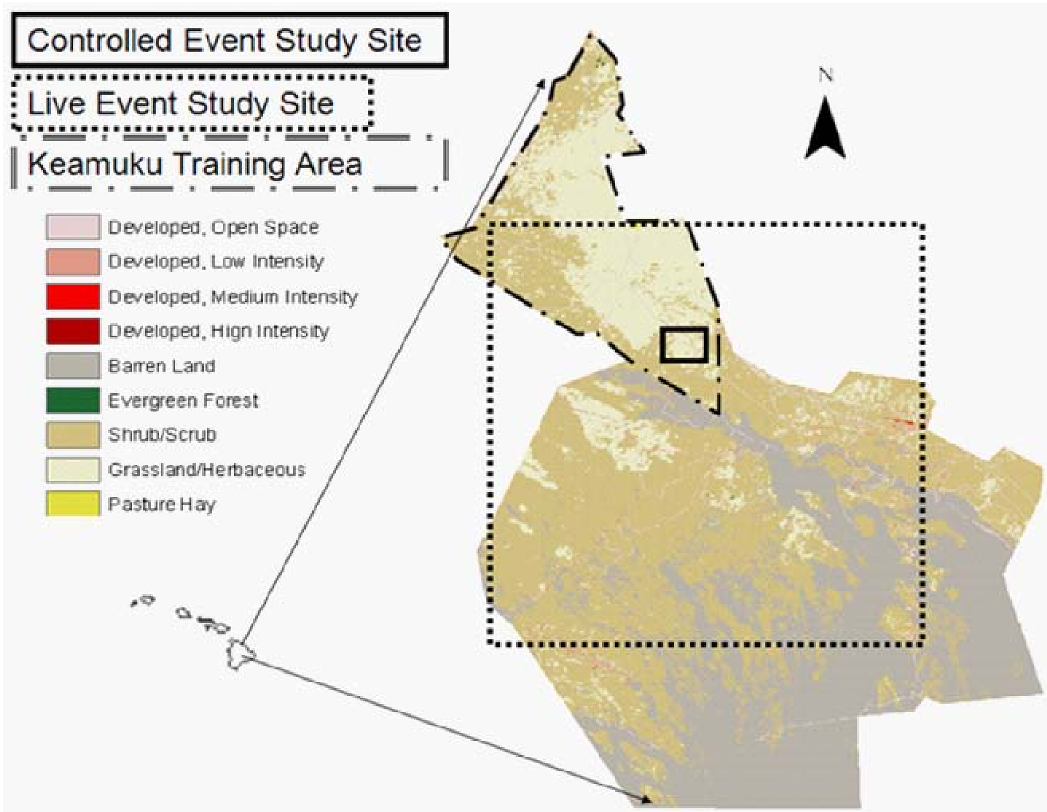


Figure 11 shows the study areas at PTA. Controlled and live training events were tracked in these areas. The field study site locations were selected through coordination with PTA installation land managers. The Controlled Event study site was located in the recently acquired Keamuku parcel. This area was of most concern to the installation land managers as it was recently opened for Stryker Brigade maneuver training. Training monitored under the live event study occurred all throughout PTA including the Keamuku Training Area.

5 Test Design

This chapter provides a description of the demonstration design, which was intended to assess performance objectives listed in Table 3 (p 22).

5.1 Conceptual test design

This section provides a broad overview of the test design used to evaluate the performance objectives. Figure 12 shows the conceptual demonstration plan. The two main demonstration sites were Fort Riley, KS and Fort Benning, GA. Fort Riley was considered an alpha test site. Fort Riley data were used in original impact model development and concept development. As such, use of impact models at this location was a test of the models within the range of conditions used in model development. Fort Riley personnel were more familiar with the approach since they had already seen data collected from the system in the past.

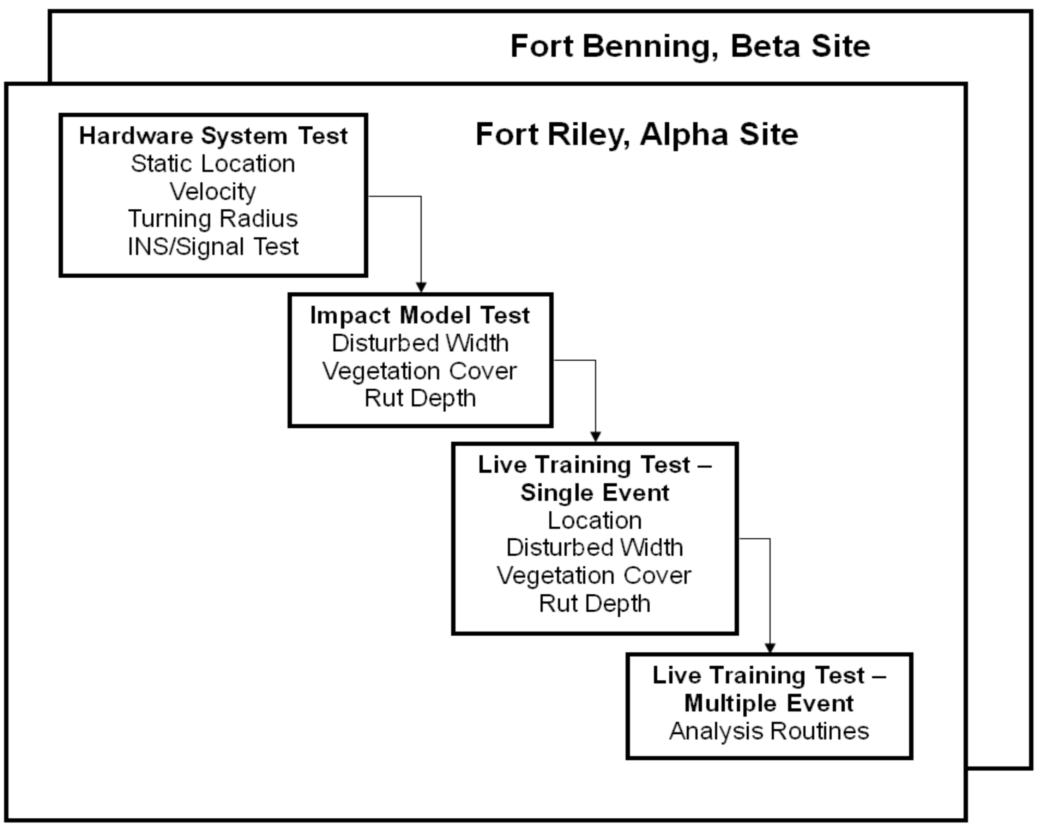


Figure 12. Conceptual demonstration plan.

Fort Benning was considered a beta test site. No data from installations in the Southeast, including Fort Benning, were used in model development. As such, this demonstration site represented an evaluation of the models outside the bounds of model development. Fort Benning personnel were also unfamiliar with the approach since they had not seen data from the system in the past. Fort Benning was included to allow use of model/technology output with other SERDP/ESTCP investments. Eglin AFB, FL was selected as a substitute for the controlled study at Fort Benning under ESTCP guidance. Additionally, installation land managers at PTA expressed interest in using the VDMTS system to identify vehicle impacts in the newly opened Keamuku Training Area. This location allowed the system to be tested and validated under different conditions and on different vehicle types.

The demonstration plan consisted of first verifying that the hardware was properly recording vehicle dynamic and static properties for use in subsequent tests. Tests were conducted for location, velocity, turning radius, and GPS signal loss (forcing INS system performance). The hardware system tests were conducted at the University of Tennessee. Results are applicable to all demonstration sites.

The second test consisted of demonstrating/validating the impact models. Vehicles of different static properties (weight, track/wheel) were driven through defined courses causing variance in vehicle dynamic properties (velocity, turning radius). Tracking units were used to capture vehicle dynamic properties and impact models were used to predict site impact (DW, vegetation cover, rut depth). Field measurements of site impacts were used to assess impact model performance. The controlled study to validate impact models was conducted at Fort Riley, Eglin AFB, and PTA. Due to the inability to access vehicles at Fort Benning, Eglin AFB was chosen as a substitute test site for the controlled study under ESTCP direction. Performing the study at Eglin AFB allowed for stressing of the models under different conditions from where they were developed. Furthermore, Eglin AFB's soil type and climate were similar to those anticipated at Fort Benning.

The third test consisted of installing tracking units on multiple vehicles during a single live training event. On completion of the training event, vehicle dynamic properties and locations were used to predict impacts along vehicle paths. Random locations were selected and site impact data were collected to validate system performance. This test was conducted at Fort Riley and Fort Benning.

The fourth test consisted of installing tracking units on multiple vehicles during multiple live training events. On completion of the training events, vehicle dynamic properties and location were used to predict spatial site impacts. Data were summarized to address one or more installation-identified land management issues. These tests were conducted at Fort Riley, Fort Benning, and PTA. Installation level technicians were trained at all locations on VDMTS unit use. This test determined the ease of system use and determined the applicability of the VDMTS unit to land management decisionmaking.

5.2 Baseline characterization and preparation

Baseline characterization and preparation was essentially the first test in the conceptual demonstration plan (Figure 12). Baseline characterization consisted of verifying that the hardware functioned properly and recorded vehicle dynamic and static properties for use in subsequent tests. Tests were conducted for location, velocity, turning radius accuracy, and GPS signal loss (forcing INS system performance). These baseline tests were performed at the University of Tennessee and the methods used are described in the following section.

5.3 Design and layout of technology and methodology components

5.3.1 VDMTS hardware positional accuracy test

VDMTS systems were located on a known benchmark (assumed location truth) and were allowed to collect a minimum of GPS position data, Coordinated Universal Time (UTC) time, and Horizontal Dilution Of Precision (HDOP) for at least 6 hours. The data were transferred from the log files to spreadsheet files for data analysis. The position data were converted to the Universal Transverse Mercator (UTM) coordinate system for analysis. The average position for the GPS points is determined by finding the average of the Northing and Easting coordinates. The position error (in meters) for each point was calculated using Equation 21, where the actual known benchmark position is denoted as the B position. The average of the position errors was determined and recorded:

$$ERROR = \sqrt{\left(A_N - B_N\right)^2 + \left(A_E - B_E\right)^2} \qquad \text{Eq 21}$$

where:

A_N = VDMTS UTM northing
B_N = benchmark UTM northing
A_E = benchmark UTM easting.

The Circular Error Probable (CEP) is the distance of GPS error that encloses 50% of the data points. The CEP was determined from position error data by determining the error distance that includes 50% of the position error distances. The Twice Distance Root Mean Square (2DRMS) is the distance of GPS error that encloses 95% of the data points' two standard deviations. The 2DRMS distance was determined from the position error data by finding the distance that includes 95% of the position error distances. The HDOP describes the clarity of which the GPS position can be determined. A high HDOP indicates a higher uncertainty of position. The average HDOP was calculated from the recorded HDOP. These measures of GPS error are measures commonly reported for GPS systems.

Several controls were used in this test: (1) high-resolution, high-cost GPS only system, (2) low-cost, low resolution GPS only system commonly used in self made vehicle-tracking units, (3) GPS/INS tracking hardware from another commercial vendor. These three controls bound the potential implementation of the impact models. Control 1 (high-resolution, high-cost GPS only system) optimized position accuracy with no GPS tracking system cost constraints. Control 2 (low-cost, low resolution GPS only system commonly used in self made vehicle-tracking units) provided comparison of using impact models with self constructed tracking units. Control 3 (GPS/INS tracking hardware from another commercial vendor) served as a reference point for other GPS/INS systems in the marketplace.

The demonstration metric was unit location within 5 m (16.4 ft) of truth. This value was based on obtaining a location value more precise than is required for impact summaries and balancing VDMTS positional accuracy with cost constraints.

5.3.2 VDMTS hardware velocity accuracy test

The VDMTS tracking units were mounted on a vehicle that was driven at three different (but constant) velocities along a track of known GPS coordinates. The velocity of the vehicle was determined by timing the vehicle with a stopwatch over a predetermined distance. The timed velocity was assumed to be truth. The velocity was also calculated from GPS/INS data by determining the change in position data of the vehicle. The same three controls used in the location test were also used in the velocity test for comparison purposes.

The demonstration metric was unit velocity within 2.24 m/s (5 mph) of truth. This value was based on obtaining a velocity value more precise than is required for impact summaries and balancing VDMTS positional accuracy with cost constraints.

5.3.3 VDMTS hardware turning radius accuracy test

The VDMTS tracking units were mounted on a vehicle that was driven around several constant radius courses (differing radii) and along a straight path multiple velocities. The distance from the center pivot to each of the course paths was used as the actual radius (truth) and was compared to the radius values calculated from the position data provided by the units. The same three controls used in the location test were also used in the velocity test for comparison purposes.

The demonstration metric was unit turning radius within 10 m (32.8 ft) of truth. This value was based on obtaining a turning radius value more precise than required for impact summaries and balancing VDMTS positional accuracy with cost constraints.

5.3.4 VDMTS hardware INS system test

The INS subsystem of the VDMTS tracking system is designed to ensure vehicle location and dynamic property values during periodic GPS signal loss or loss of GPS signal quality. The same three controls used in the location test were used in the velocity test for the same comparison purposes. Tracking units were mounted on a vehicle that is driven through tunnels, vegetation, and other areas of poor or no GPS signal. The location, velocity, and turning radius along the course with and without signal were recorded.

The demonstration metric was location, velocity, and turning radii for areas of no or low GPS signal quality. This was essentially a preliminary test to ensure the INS system was functioning properly. A test of the value of having INS included in the VDMTS is in Section 5.4.2, "Live training test—Model validation."

5.4 Field testing

5.4.1 Controlled impact model validation study

A series of field studies were conducted using multiple vehicles (M1A1 Abrams Tank, Armored Personnel Carrier (APC)-M113, M2A2 Bradley, High-Mobility Multipurpose Wheeled Vehicle (HMMWV), HEMTT, and Stryker Light Armored Vehicle (LAV) III) (Table 4). These vehicles covered a range of tracked (light to heavy) and wheeled vehicles (light to heavy and multiple axles). Since the impact models were designed for use with various types of vehicles and incorporate vehicle static properties (weight, track/wheel), vehicles that represent a range in vehicle static properties were appropriate for model validation testing.

Each vehicle was driven on a systematically planned course (spiral) within a randomly located treatment plot (Figure 13). Each vehicle tracked three treatment plots (replication). Each spiral course within a treatment plot consisted of a section of straight-line travel followed by a section of constantly decreasing turning radius. The spiral was completed after reaching the vehicle's minimum turning radius. One spiral for each vehicle was traversed at a slow and fast velocity. Actual velocities were not critical as long as they represent different velocities for testing the model and are reasonable velocities for operation of a vehicle of that type. The slow velocity typically represented an average velocity for off-road travel for that vehicle while the high velocity condition represented the maximum velocity the driver could safely maneuver the spiral course.

A VDMTS hardware unit and a high-cost, high-resolution GPS tracking unit were mounted on each vehicle tested. The high-cost, high-resolution GPS tracking unit was the same unit as the number 1 control in Section 5.2 (hardware tests, pp 49–51). This control was to relate data back to data collected from hardware tests and as a quality control check on the VDMTS.

Table 4. Vehicles tested in controlled impact study at each site.

Site	Test Dates	Vehicle Types Tested
Fort Riley	12-13 Aug 2008	M1A1, M113APC, HMMWV, HEMTT
PTA	6-9 Nov 2009	Stryker LAV III
Eglin AFB	12 May 2010	M2A2, HEMTT

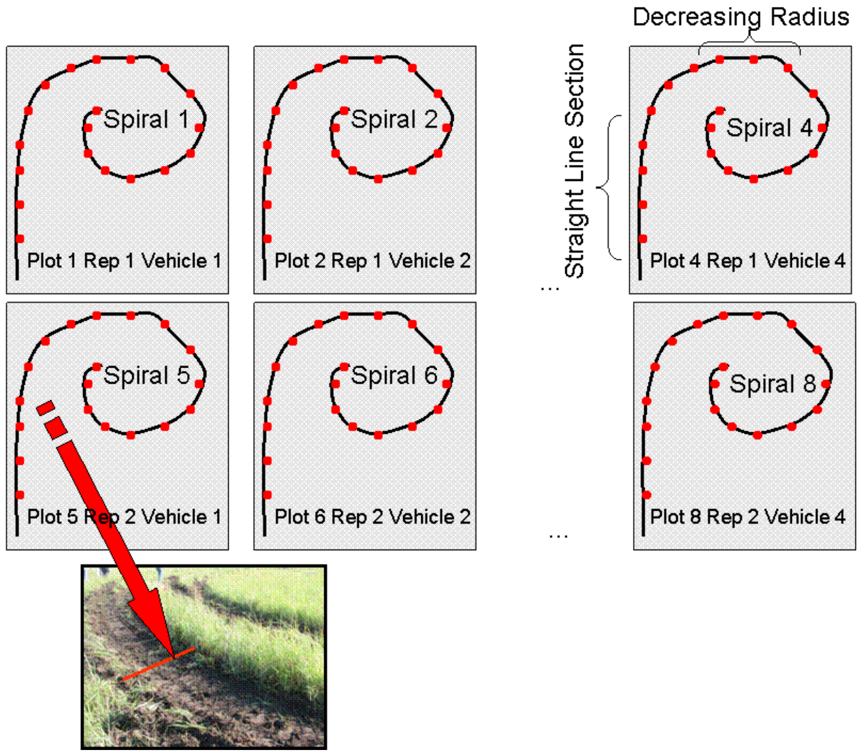


Figure 13. Field test study design. Spirals show vehicle courses. Dots show measurement plots. Arrow shows an example of a sample point. The line across the vehicle track illustrates a measurement transect.

The exact location of the study within the installation was determined on availability of site, relatively undisturbed soil/vegetation, and representative of lands typically used for training. Relatively undisturbed soil/vegetation was chosen to allow for consistent measurements within a treatment. The three demonstration sites (Fort Riley, Eglin AFB, and PTA) ensured testing over a broad range of soil/vegetation types.

5.4.2 Live training test—Model validation

A field study was conducted by tracking a live training event using VDMTS systems at Fort Riley and Fort Benning. Military training events were identified through coordination with installation personnel. The military training events tracked were based on availability of units training at the installation, access to unit equipment, duration of training, number of vehicles, types of vehicles, mission doctrine, training areas scheduled, and installation objectives for study. The intent of these selection criteria was to identify a training mission tested the VDMTS hardware and impact models. The

events included: (1) four vehicle types, (2) on- and off-road activity, (3) wide range of site conditions used, and (4) 5- to 10-day durations.

A number of vehicles were instrumented (Table 5) with VDMTS hardware at both sites. Tracking units were installed in the motor pool and removed after the event is completed. VDMTS data were used to locate vehicle tracks within a few days of the completion of training. Sample locations were randomly located along vehicle paths. Measurements of site damage (DW, vegetation loss, rut depth) were made at each sample point using methods described in Section 5.5, below. Predicted site damage (DW, vegetation loss, rut depth) were compared with measured site damage to quantify the ability of the VDMTS to predict overall site damage for a training event.

In addition, data from the model validation live training test were used to quantitatively assess INS performance without GPS signal. Data from the single event study were analyzed with and without INS data being forced to the GPS signal, which allowed a measurement of INS data error to be compared with the GPS signal.

5.4.3 Live training test—Multiple events for system validation

A field study was conducted by tracking a series of live training events using VDMTS systems (Table 6). (Appendix B includes a comprehensive table of vehicles tracked by date and location.) A series of military training events were identified through coordination with installation personnel. The military training events tracked were based on an installation defined issue that relates to vehicle impacts on installation lands. A minimum of four training events were tracked per installation with a total of 14 events tracked over 3 years.

Table 5. Vehicles tested during live training event model validation.

Site	Test Dates	Vehicle Types Tested	# Vehicles Tested
Fort Riley	17-21 Aug 2009	HMMWV, Buffalo, Medium Tactical Vehicle (MTV)	18
Fort Benning	31 Oct - 9 Nov 2011	HMMWV, Stryker LAV III	20

Table 6. Events tracked during multiple live training events phase of study.

Site	Test Dates	# Days	Vehicle Types*	# Vehicles
Fort Riley	17-21 Aug 2009	5	HMMWV, Buffalo, MTV	18
Fort Riley	13-15 Jul 2010	3	HMMWV, MTV	7
Fort Riley	10-17-May2011	8	HMMWV, HEMTT, LMTV	12
Fort Riley	17-22 May 2011	6	HMMWV, HEMTT, LMTV	11
Fort Benning	18-20 Oct 2010	3	Stryker, Bradley	9
Fort Benning	28-29 Mar 2011	2	Stryker, Bradley, M1A1, HMMWV	7
Fort Benning	31 Oct - 9 Nov 2011	10	Stryker, HMMWV	20
Fort Benning	9-14 Nov 2011	6	Stryker, HMMWV	22
PTA	6-9 Nov 2009	4	Stryker	3
PTA	24-29 Jan 2010	6	AAV	6
PTA	17-23 Jan 2011	6	AAV	6
PTA	8-10 Jun 2011	3	AAV	2
PTA	13-14 Jun 2011	3	AAV	6
PTA	16-17 Jun 2011	2	AAV	7

* AAV = Amphibious Assault Vehicle
Bradley = American infantry fighting vehicle
HEMTT = Heavy Expanded Mobility Tactical Truck
HMMWV = High-Mobility Multipurpose Wheeled Vehicle
LMTV = Light Medium Tactical Vehicle
M1A1 = M1 Abrams battle tank
MTV = Medium Tactical Vehicle
Stryker = A family of eight-wheeled, 4-wheel-drive (8x4), armored fighting vehicles

Prior to the first field event, installation technical staffs were trained on: (1) installation and use of VDMTS hardware, (2) QA/QC of VDMTS data, and (3) analysis of VDMTS data. During the training courses, training times were recorded for each activity. The contents of the training courses are outlined on below. The User's Manual (included in the Appendix C) gives more detailed descriptions of hardware and software use, trouble-shooting, and post processing of the VDMTS data. Installation technical staff were given these VDMTS user manuals, which describe every aspect of the program:

- Installation and use of VDMTS Hardware:
    1. Proper installation of the VDMTS unit including proper unit orientation and mounting locations on military vehicles
    2. Test documentation - Recording VDMTS number and vehicle number, type, and mission on vehicle-tracking sheet

3. VDMTS unit operation in both logging modes, Auto (Default) and Manual Logging
4. VDMTS unit shutdown and documentation (record flashing lights and battery voltage)
5. Downloading data from VDMTS (via Universal Serial Bus [USB] cable or Secure Digital [SD] card removal)
6. VDMTS unit maintenance (e.g., checking battery voltage levels, charging batteries, replacing parts)
7. VDMTS unit troubleshooting.

- QA/QC of VDMTS Data:
    1. Opening of archive file (.vdm) file on computer to verify completeness (Examining start and stop times to make sure file is complete – size of the file can be an indication of logging times)
    2. Proper format of archive file (.vdm) file and recognition of corrupted file
    3. Confirming that adequate vehicle positional accuracy was obtained
    4. Installation of VDMTS software
    5. Processing raw archive file (.vdm) files to read inertial and GPS data strings.

- Analysis of VDMTS Data:
    1. Processing data to determine vehicle velocity and turning radius
    2. Converting to UTM (meters), determining velocity and distance traveled from GPS point movement, determining turning radius using 3-point method
    3. Using vehicle position, velocity, and turning radius data to calculate impact severity, DW, vegetation removal, and off-road time depending on user needs
    4. Compiling and summarizing findings in a useable format
    5. VDMTS software and data troubleshooting.

For each training event, approximately 10-20 vehicles were instrumented and tracked depending on the training event selected and the number of vehicles in each event. In several events, the total number of vehicles was fewer than 10 so all vehicles were tracked. Selection of vehicles for tracking was based on input from installation military and natural resources personnel. Military personnel provided input on vehicle use as related to doc-

trine. Natural resources personnel helped relate vehicle selection to natural resource decisionmaking issues. Several uses for VDMTS derived data at both installations are described at the end of this section. Tracking units were installed in the motor pool before each event. Units were installed according to the VDMTS User's Manual. Tracking units were removed after each event is completed. The mounting and removal times for VDMTS units were monitored and recorded. Vehicles were tracked for the duration of the training event. Training events were expected to last approximately 1 week, but varied by training mission and event. There was no field data collection (vegetation loss or impact severity) associated with this demonstration beyond vehicle dynamic properties data and positional data quality collected by the VDMTS systems. Previous testing had already validated system performance in terms of predicting site impacts (Section 5.2, p 49).

Technician-level individuals performed data QA/QC and analyzed the data according to the steps listed previously. Technician data analyses times were recorded throughout this process. Data were compiled and summarized to aid in land management decisions or to parameterize related models as described in Sections 3.8 (p 32) and 3.10 (p 36).

At Fort Riley, these data aided in the identification of LRAM sites, low water crossing usage, and emerging trails. This allowed resources to be focused on regions with more intense usage. An ESTCP project titled "Kinematic wave approach for rapid soil erosion assessment" has developed a Kinematic Wave model currently in use at Fort Riley to predict erosion and gully formation. By incorporating vegetation removal calculated using the VDMTS with existing land-use/landcover datasets, predictions that are more reliable were obtained (See description of Metric 3.1 in Section 3.3 [p 28] for more details).

For Fort Benning, the land management issue was determining the impact of changes in installation training requirements associated with BRAC actions on RCW populations. This involved collecting vehicle use data to quantify the amount of time vehicles trained near cavity trees and in foraging areas. The use of the VDMTS data in this evaluation of resulted in data currently not collected using traditional field data collection methods for RCW impact assessments.

The data collected at PTA were used to identify LRAM sites and identify potential trail networks for hardening. PTA recently had opened the Keamuku Maneuver Area for off-road training. PTA LRAM was interested in using the VDMTS process to obtain a gross estimation of Stryker Brigade impacts to the maneuver area. Dust and air quality are also issues at PTA. Tracking of vehicles at PTA allows for estimation of dust generation and comparison against measured levels.

5.5 Sampling protocol

5.5.1 Sampling protocol for metric evaluation

5.5.1.1 Controlled event study

Vehicle impacts (i.e., DW, vegetation loss, and rut depth) were measured immediately after tracking. All measurements were made along the outer track (for standardization) of each spiral (Figure 13, p 53). The first sample location was randomly located within the first 10 m (32.8 ft) of the straight-line tracking portion of each spiral. Subsequent samples were systematically located approximately every 5 m along the vehicle track resulting in approximately 15 sample points per spiral. DW was measured perpendicular to the vehicle track and encompassed the area where soil and/or vegetation were impacted by the vehicle tire/track. The DW included areas where vegetation was flattened (but not killed) and areas where soil was removed or piled up. DW was recorded at each sample point. Vegetation cover was estimated using a line transect established perpendicular to the track (same measurement line as the DW measurement).

A second line transect was established perpendicular to the track and adjacent to the track. Each undisturbed paired transect was located to the outside of the spiral in untracked vegetation and is of the same width as the disturbed transect. For each line transect (within track and adjacent to the track), bare ground was visually estimated and reported as a percent of transect length. Vegetation loss is the difference between the two values. Vegetation loss was measured at each sample point. Rut depth was measured using a ruler laid horizontally across the outside track from undisturbed soil on the inside of the track to undisturbed soil on the outside of the track. A second ruler measured the deepest portion of the rut. Rut depth was measured at each sample point. A drop cone measurement was taken at each location to measure surface cone index.

Sample points were measured as paired sample locations within the track and outside of the track. Pre-disturbance measurements were not taken due to the inability to accurately predict the location and width of the disturbed area. Due to the difficulty of trying to maintain a constant velocity and decreasing turning radius, drivers were frequently unable to follow exactly pre-marked courses. This sampling approach assumes that the disturbed area and adjacent undisturbed area have the same pre-disturbance cover.

The line transect used to measure vegetation cover and rut depth was not a fixed length. The line transect was the width of the disturbed track (DW). This width varied across the course usually varying from the width of a track (or tire) in straight sections to several track (or tire) widths in sharp turns.

Site characterization data were collected in the undisturbed transect location. Soil moisture was recorded with a Time Domain Reflectometry (TDR) soil moisture probe. A drop cone measurement was taken at each location to measure surface cone index. Additional site characterization data were collected at three sample points. The sample points were 3 (straight), 8 (moderate turn), 15 (sharp turn). Above ground biomass, below ground biomass, soil texture, bulk density, and soil moisture (gravimetric) were measured. Above ground biomass was measured by clipping all vegetation above ground in a ¼ m^2 frame. Biomass was oven-dried and weighed. Below ground biomass was collected from a sample obtained from a soil core for the top 10 cm. Roots were removed by washing and oven-dried and weighed. Soil moisture and texture were obtained from a soil core for the top 10 cm. Soil moisture was the percent moisture before and after oven drying. Texture was obtained by sieving the oven-dried soil sample. Torsional shear strength was measured with a Cohran torsional shear-graph. Cone index was measured for the soil profile with a cone penetrometer. These data were used to supplement the drop cone measurements take at each sampling point (described above) that more accurately measure cone index near the soil surface.

5.5.1.2 Model validation live training event study

Event tracking consisted of instrumenting between 10 and 20 vehicles with VDMTS systems and tracking a live training event. The installation selected the live training events with the intent of having multiple vehicle types training across a range of site conditions typical of the installation.

Tracking units were installed on vehicles in the motor pool. Tracking units were removed after the event is completed. The intent was to monitor a minimum of 10 vehicles for sampling purposes. Additional vehicles were tracked when possible in case of hardware failure, vehicle failure, or where training doctrine resulted in some vehicles with little off-road travel.

Field study preparation included downloading VDMTS data into a GIS data management system. Vehicle paths were combined with an installation GIS roads data layer. Off-road vehicle travel was identified. The resulting off-road vehicle paths constitute the population for sampling. For off-road travel areas, vegetation loss (DW, impact severity, and cumulative impact) and rut depth were estimated using the VDMTS models. Vehicle paths were loaded into high-quality GPS units for use in field data collection.

Primary field data collection consisted of using high-quality GPS units to follow previously driven vehicle paths. Existing vehicle paths were driven/walked. When vehicle paths went off-road, samples were taken. Sample locations were based on the GPS location and visual location of the vehicle track. This sampling allowed for an unbiased comparison of actual and predicted vegetation loss, impact severity, and rutting. The primary sampling was representative of actual training and site conditions.

Measurements were taken at each sample location. GPS location was obtained from high-quality GPS unit of the sample plot location. DW, IS, and rut depth were measured as described above. Site characterization data were also collected as described previously in Section 5.5.1.1, "Controlled event study" (p 58).

Sample points were measured as paired sample locations within the track and outside of the track. Pre-disturbance measurements were not taken due to the inability to predict the location of the disturbed areas before the training event. This sampling approach assumes the disturbed area and adjacent undisturbed area have the same pre-disturbance cover.

5.5.1.3 Multiple live training event study

A subset of the total number of events scheduled for the installation for the year was sampled at each location. Specific events were selected that address the management issue identified for the installation. A subset of the

total number of vehicles in an event was evaluated so the subset of vehicles was representative of the whole training event. This allowed data from the subset to be extrapolated to the whole event. The sampling accounted for differences in units and vehicle types.

For each training event, approximately 10-20 vehicles were instrumented and tracked depending on the training event selected and the number of vehicles in each event. In several cases, the number of vehicles in the training event was less than 10 so all vehicles were tracked. Selection of vehicles for tracking was based on input from installation military and natural resources personnel as described in the previous section. Military personnel provided input on vehicle use as related to doctrine. Natural resources personnel helped to relate vehicle selection to the decisionmaking process.

5.5.2 Calibration of equipment

Individual VDMTS tracking units require an initial calibration process to account for slight differences in INS system sensors. Each unit was calibrated by Cybernet before use in the demonstration project. Calibration is a one-time process conducted at Cybernet facilities prior to delivery of the units. After purchase/delivery of the VDMTS hardware, no additional calibration is needed.

5.5.3 Quality assurance sampling

The VDMTS system relates positional accuracy in terms of HDOP and age of differential correction. This allowed each data point to be analyzed for positional accuracy and quality assurance. VDMTS vehicle dynamic property data collection was also supplemented with high-cost, high-quality GPS systems in the controlled study as backup systems and validation dataset.

5.5.4 Sampling documentation

Standardized field data sheets were used to document vehicle ID, type, and mission, and the VDMTS unit ID mounted on each vehicle. All field data were combined from all three collaborators and archived at each location. VDMTS tracking data were stored in text format, shared among all three collaborators, and archived by all three collaborators. Standardized training documentation sheets were used to document technician training times and times required for technicians to perform each step of VDMTS process.

5.6 Sampling results

5.6.1 Hardware tests

The first component of the controlled field study demonstration plan was to validate the hardware is properly functioning and recording vehicle dynamic and static properties for use in subsequent tests. Tests conducted included location, velocity, turning radius, and under heavy cover (forcing INS system performance). The hardware system tests were conducted at the University of Tennessee. Results are applicable to all demonstration sites (Fort Riley, Fort Benning, Eglin AFB, and PTA).

For the static positional test, the VDMTS system was compared against three other GPS systems. An additional INS/GPS system was also tested to analyze system performance. Average distance error (m), CEP, the 2DRMS were all calculated (Table 7). The VDMTS system was the worst performing of the five systems tested. This was because the GPS signal in the initial VDMTS system was not differentially corrected. The other units tested all used differential correction to increase the positional accuracy. A GPS system capable of Wide Area Augmentation System (WAAS) differential correction replaced the previous GPS system in the VDMTS. The static position evaluation test was repeated. Figure 14 shows a plot of the VDMTS unit longitudinal and latitudinal error (in meters) over the 6-hr test, in which the origin (0,0) represents the true location of the tracking systems. Table 8 lists the test results using the upgraded VDMTS system.

A velocity evaluation test was performed on the VDMTS system as described in Section 5.3.2 (p 50). Table 9 lists the results from the velocity evaluation test. The truth value represents the actual measured velocity while the VDMTS values represent the VDMTS calculated velocity.

Accuracy of turning radius was measured by mounting the units on a cart pushed at two velocities on the track with a range of known turning radii as described in Section 5.3.3 (p 51). Figure 15 shows of graph of the data collected and Table 10 summarizes the results.

The final success criteria for the first performance objective was to determine ability to record in situations when GPS signals were not available due to topography, vegetation, and related conditions. This was tested by driving the unit through a tunnel and under canopy. Results show that the INS data collected from the Vehicle Dynamics Monitor (VDM) hardware increase the accuracy when compared to systems without INS capability (Table 11).

Table 7. Initial position evaluation tests (m).

Metric	VDMTS	INS/GPS	G18	T132	T332
Average	7.39	4.25	2.48	1.72	0.06
CEP	6.94	2.58	2.58	1.14	0.06
2DRMS	12.13	3.90	3.90	4.55	0.10

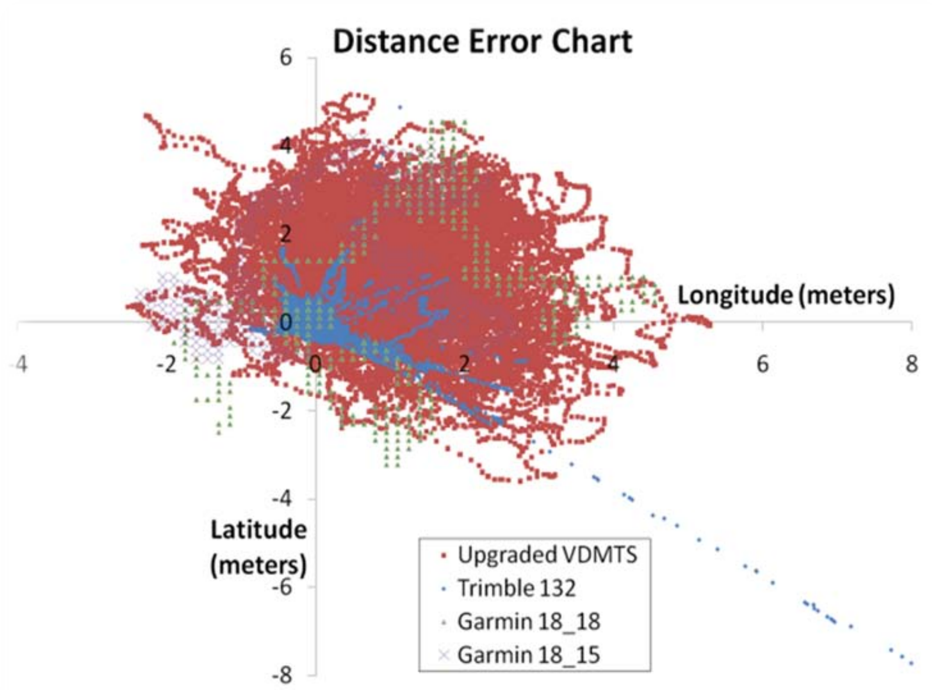


Figure 14. Positional error tests with upgraded VDMTS hardware.

Table 8. Upgraded VDMTS position evaluation tests (m).

Metric	VDMTS (upgraded)	VDMTS (initial)	G18 (#1)	G18 (#2)	T132
Avg. error (m)	2.05	7.39	2.11	2.75	0.28
CEP (m)	2.00	6.94	1.89	3.04	0.20
2DRMS (m)	3.71	12.13	3.74	4.44	0.64
Avg. HDOP	0.9	NA	1.1	1.0	1.1
Avg. SAT No.	10.5	NA	8.3	8.3	7.7
DGPS %*	100	NA	100	100	100
*DGPS = Differential Global Positioning System					

Table 9. Velocity evaluations (m/s).

Test	Truth (m/s)	VDMTS (m/s)	Error (m/s)	Error %
1	1.43	1.47	-0.04	3.00
2	1.62	1.76	-0.14	8.64
3	1.40	1.43	-0.03	2.19
Average	1.48	1.55	-0.07	4.80

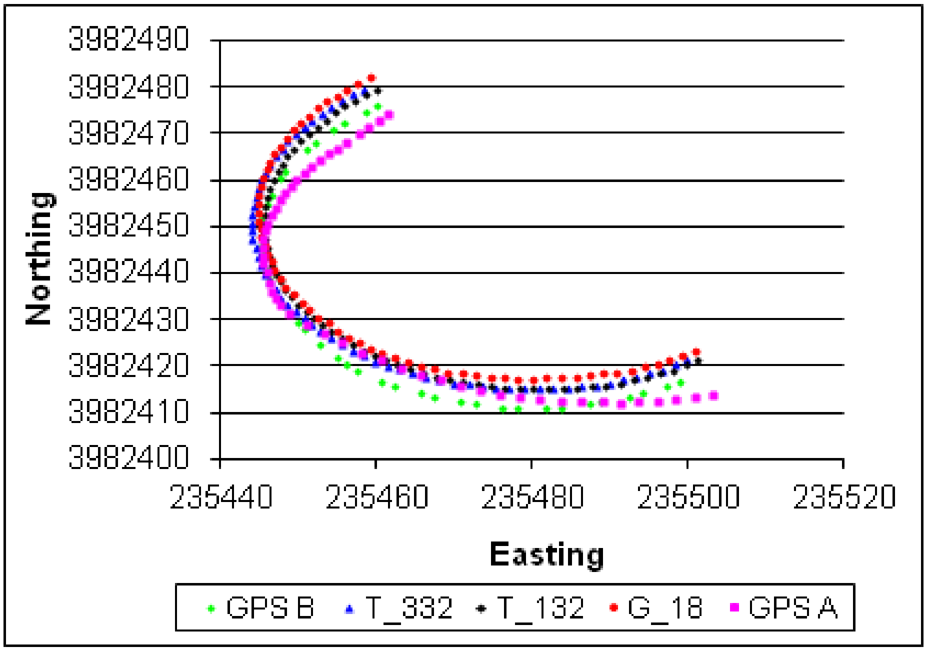


Figure 15. Turning radius evaluation tests (m).

Table 10. Turning radius evaluation tests (m).

Velocity	Actual TR	VDMTS	INS/GPS	G18	T132	T332
Slow	6.7	6.5	4.0		4.0	
Slow	10.5	10.8	6.7		6.1	
Slow	18.6	20.0	10.9		14.1	
Slow	38.0	62.3	54.0	53.8	62.0	49.7
Slow	48.0	48.4	59.0	47.2	65.8	72.3
Fast	38.0	49.4	39.8	48.8	38.9	39.3
Fast	48.0	58.5	46.1	55.3	50.2	54.4

Table 11. Positional error under heavy cover test.

GPS System	Average Distance Error (m)	Standard Deviation (m)
Trimble (without INS)	2.7	0.25
Garmin (without INS)	2.7	0.34
VDM	2.2	0.17

5.6.2 Controlled test model validation

The main objective of the controlled test as to validate that the impact models accurately predicted site impacts based on vehicle dynamic properties. Tests conducted included DW, vegetation loss, and rut depth measurements. These tests were performed using multiple vehicles at Fort Riley, PTA, and Eglin AFB. The theoretical model results were compared with measured impact values. Additionally, measured impact values were used to develop site-, vehicle-, and condition-specific statistical models (Figure 16 and Table 12). These statistical models represent the best prediction possible with the variability observed and are a current method of impact assessment.

A linear regression of the predicted vs. measured data was performed to determine the closeness to a unity slope. Using this as an indicator of model quality, the DW statistical model performed slightly better than the theoretical model at Eglin AFB and PTA, but not at Fort Riley (Figures 17–19).

Using linear regression as an indicator of model success, the statistical IS (vegetation removal) models slightly outperformed the theoretical models for the controlled studies (Figures 20-22). Given the intended use of the models, a more appropriate measure of model validation is the average error between the predicted and measured impacts using each model (Table 13). Since the models are intended to quantify impacts over an entire training event, the errors were calculated over the entire controlled study at each location.

The statistical models predicted DW and IS better than the theoretical models in five of the six instances (Figures 17-22). This observation is expected since the measured data were actually used to develop the statistical models in this case. A separate dataset would need to be collected to assess unbiased statistical model performance under the controlled study.

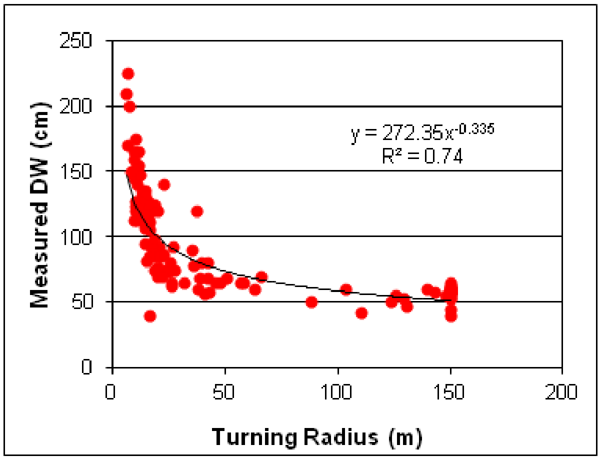


Figure 16. Example of statistical regression model developed for Stryker vehicle at PTA.

Table 12. Statistical regression models developed during controlled study.

Site	Vehicle	Regression
Fort Riley	M1A1	DW = 295.36(TR)$^{-0.188}$
Fort Riley	M1A1	IS = 241.92(TR)$^{0.349}$
Fort Riley	APC-M113	DW = 126.54(TR)$^{-0.208}$
Fort Riley	APC-M113	IS = 210.12(TR)$^{-0.445}$
Fort Riley	HMMWV	DW = 172.94(TR)$^{-0.262}$
Fort Riley	HMMWV	IS = 17.85(TR)$^{-0.096}$
Fort Riley	HEMTT	DW = 792.94(TR)$^{-0.47}$
Fort Riley	HEMTT	IS = 210.12(TR)$^{-0.445}$
Eglin AFB	M2A2	DW = 372.78(TR)$^{-0.271}$
Eglin AFB	M2A2	IS = 378.53(TR)$^{-0.571}$
Eglin AFB	HEMTT	DW = 1373.5(TR)$^{-0.571}$
Eglin AFB	HEMTT	IS = 10.74(TR)$^{-0.013}$
PTA	Stryker	DW = 272.35(TR)$^{-0.335}$
PTA	Stryker	IS = 108.71(TR)$^{-0.456}$

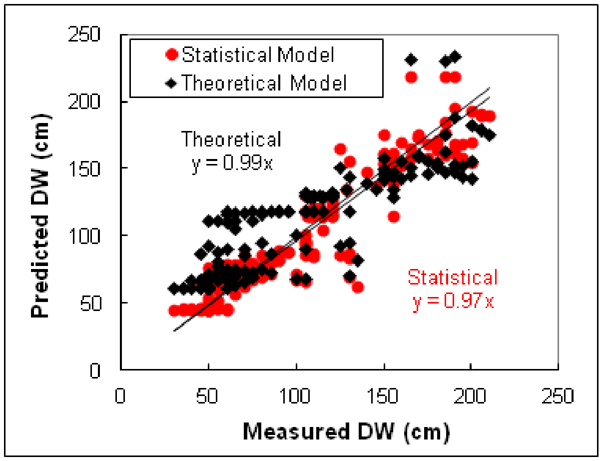


Figure 17. Theoretical and statistical model predicted DW values compared with measured values for Fort Riley controlled study.

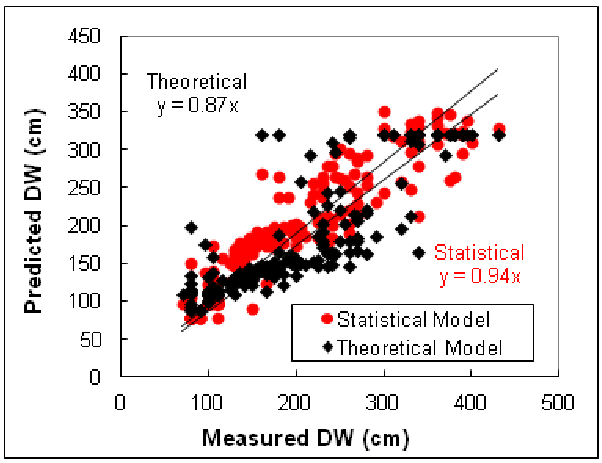


Figure 18. Theoretical and statistical model predicted DW values compared with measured values for Eglin AFB controlled study.

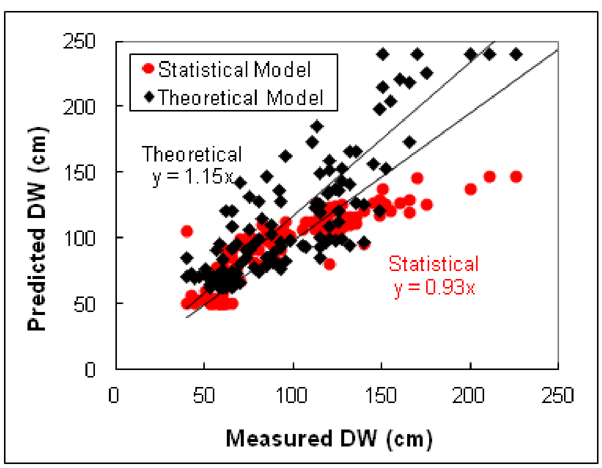


Figure 19. Theoretical and statistical model predicted DW values compared with measured values for PTA controlled study.

Table 13. Average absolute error between predicted and measured values for theoretical and statistical models.

Error		Riley			Eglin AFB			PTA		
		DW*	IS*	RD	DW	IS	RD	DW	IS	RD
Theoretical	Average Absolute Error	22.0	9.8	1.1	33.9	9.8	0.1	22.4	13.4	0.7
	Average Error	-7.7	-3.7	1.0	17.4	-8.2	-0.1	-16.2	11.9	0.6
Statistical	Average Absolute Error	13.0	11.5	3.9	24.2	7.5	0.9	14.8	10.8	1.0
	Average Error	1.5	1.9	-3.9	-0.8	0.5	-0.9	2.3	3.3	0.1
* Units are cm for DW rut depth [RD] and percentage for impact severity [IS].										

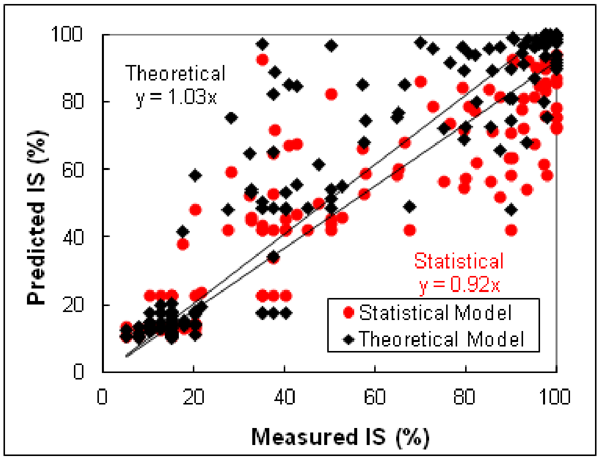


Figure 20. Theoretical and statistical model predicted IS values compared with measured values for Fort Riley controlled study.

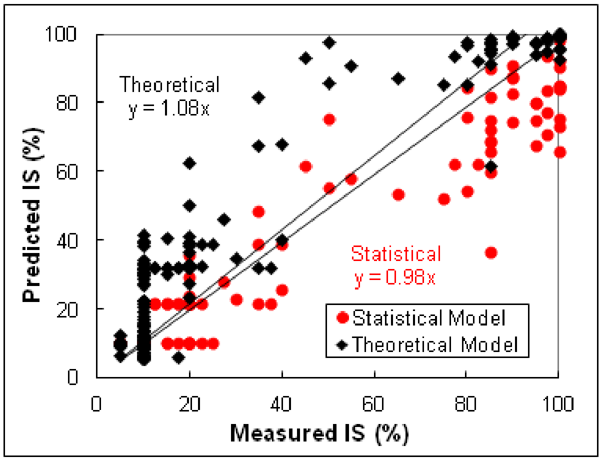


Figure 21. Theoretical and statistical model predicted IS values compared with measured values for Eglin AFB controlled study.

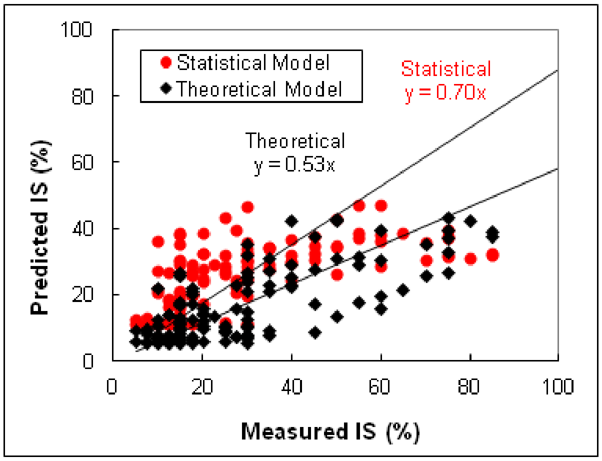


Figure 22. Theoretical and statistical model predicted IS values compared with measured values for PTA controlled study.

5.6.3 Single live training event study and model validation

VDMTS hardware and models were tested in live training events by tracking a live training event at Fort Riley and Fort Benning. VDMTS data were used to locate vehicle tracks following the training event. Measured impacts from these tracks were compared with model predicted values. The statistical models developed at both sites were also used to predict impacts. The theoretical predicted values were compared against the impacts measured in the field as well as the statistical model predicted values (Figures 23-26).

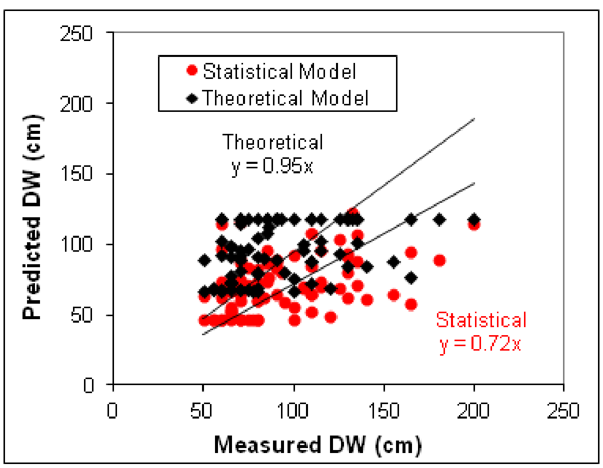


Figure 23. Theoretical and statistical model predicted DW values compared with measured values for Fort Riley live training event study.

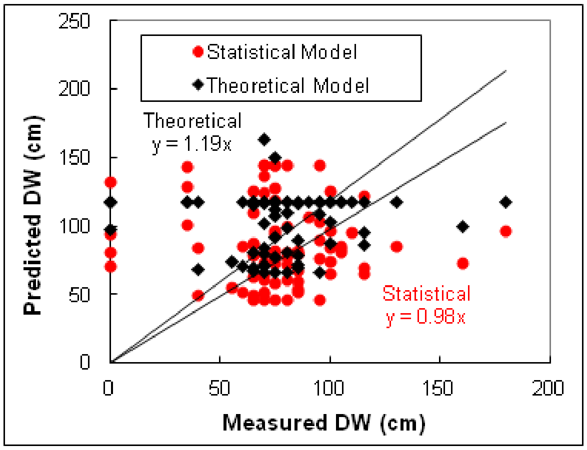


Figure 24. Theoretical and statistical model predicted DW values compared with measured values for Fort Benning live training event study.

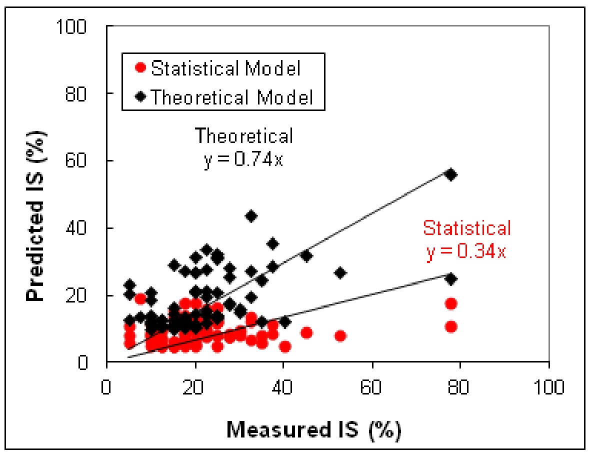


Figure 25. Theoretical and statistical model predicted IS values (vegetation removal) compared with measured values for Fort Riley live training event study.

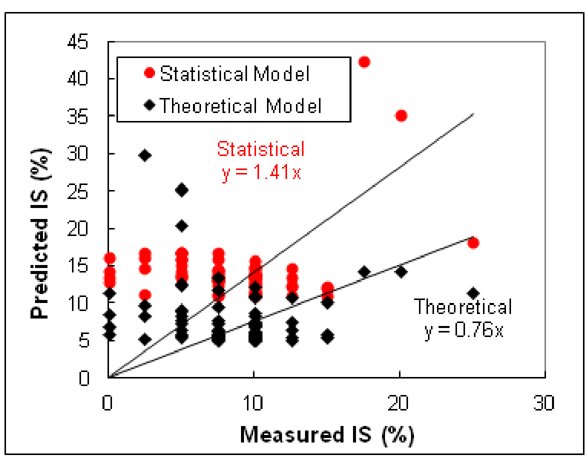


Figure 26. Theoretical and statistical model predicted IS values (vegetation removal) compared with measured values for Fort Benning live training event study.

The agreement between predicted and measured values is generally lower for the live training events compared with the controlled events when looking at the slope of the linear regression model (Figures 23–26 vs. Figures 17–22). These measurements were taken across the landscape with varying terrain and vegetation giving more variability than in the relatively flat, homogeneous vegetation cover observed in the controlled studies. The theoretical models could likely be improved by incorporating a slope or terrain factor. However, this would also make model use more data intensive and increase implementation costs.

Even though the regression between predicted and measured was not as good for the live event study, the average absolute errors for the theoretical models in the live training event study are comparable to the errors measured in the controlled study (Table 14). The controlled studies were designed to provide a large range of velocities and turning radii to stress the models. However, from the two live training events, it appears that most of the off-road training occurred in a smaller range of turning radii and at velocities that resulted in a smaller range of DW and IS, which explains why the average absolute errors remained similar despite the poorer regression.

While the statistical models performed better than the theoretical models in the controlled study, the theoretical models performed as well as statistical models in the live single training event study. In practice, this means that the theoretical models may perform as well as site-specific statistical models in estimating impacts from a military training event. Before using this methodology, a separate study would have been required to develop an empirical model for each site being tested resulting in added study costs. The theoretical model removes this necessity while providing an estimate of the training event impacts.

Table 14. Absolute average errors between predicted and measured impacts for live training events.

	Fort Riley			Fort Benning			Combined		
	DW	IS	RD	DW	IS	RD	DW	IS	RD
Theoretical	24.8	7.7	0.7	34.8	4.9	0.0	29.7	6.3	0.4
Statistical	27.2	12.9	0.9	32.6	6.4	0.5	29.7	8.3	0.7

In addition to modeling performance, hardware durability and positional accuracy were assessed in the single live training event tests. Table 15 summarizes the total training time, recorded time, and percent of total training time for each training event.

The positional accuracy was calculated by comparing the location of the tracks in the field with the VDMTS collected data at Fort Riley and Fort Benning. At Fort Riley, the observed positional accuracy was 1.6 m (± 0.1 m). At Fort Benning, the observed positional accuracy was 1.1 m (± 0.1 m). At several instances during the live training event at Fort Riley, the GPS signal was lost. In these cases, the VDMTS INS system succeeded in calculating vehicle location. Figure 27 shows one instance where the GPS lost reception and INS calculated the vehicle location. In this instance, the GPS signal was lost for over 700 m. The blue line indicates the INS vehicle location while the red line shows GPS predicted points. The GPS system assumed the vehicle path was a straight line during the GPS signal loss.

To quantitatively assess INS performance without GPS signal, data were analyzed with and without INS data being forced to the GPS signal. This allowed a measurement of INS data error compared with the GPS signal. A subset of 10 out of the 38 single live training event vehicle files (48259 sampling points) was analyzed for INS performance. In the subset of 10 vehicles, the positional accuracy never exceeded the 10 m threshold signifying the success criterion was met. The average error compared with the GPS signal was 0.164±0.002 m. Across the 48,259 samples, the maximum error compared with the GPS signal was 2.60 m.

Table 15. Summary of hardware durability (training time recorded) from single live training events.

Installation	Total Time (hrs)	Recorded Time (hrs)	% Recorded
Fort Riley	1800.0	1489.1	82.7
Fort Benning	209.6	209.7	100.0
PTA	628.0	556.0	88.5
TOTAL	2637.6	2254.8	85.5

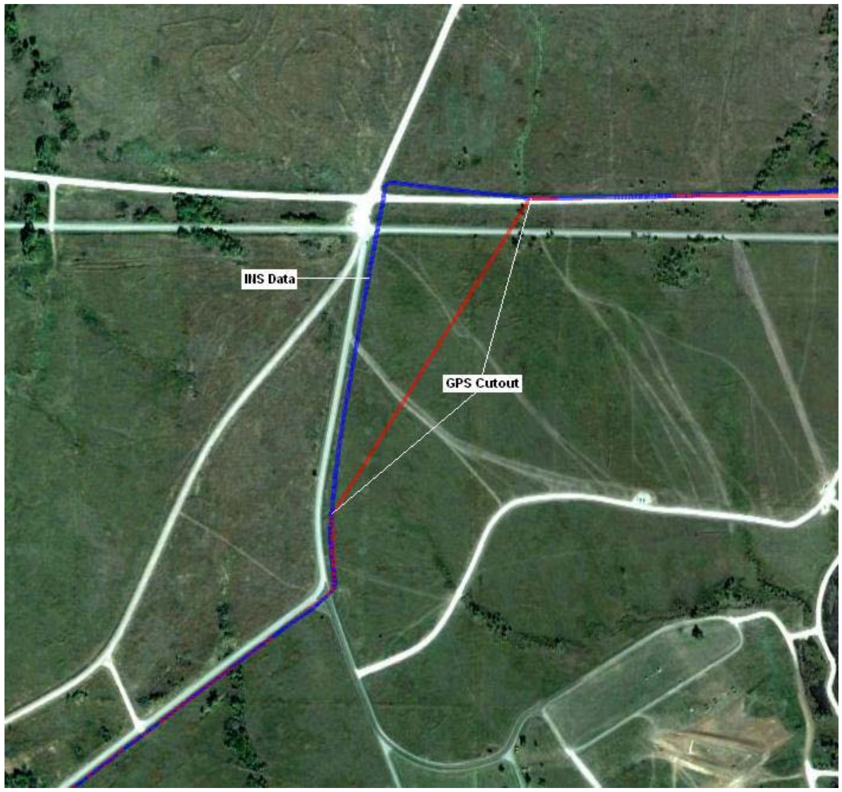


Figure 27. INS vehicle location during GPS signal loss.

5.6.4 Multiple live training event tests

As described in Section 5.4.3 (p 54), a field study comprised tracking multiple training events (Table 6, p 55) was performed for system validation. The main objective of this phase of the demonstration was to test and validate the usability of the system (hardware, models, and results) and demonstrate the ability for the results to aid in military land-use decisionmaking. In addition to the actual vehicle-tracking and impact data from the training events, data were collected to assess hardware durability and ease of system use.

5.6.4.1 Multiple live training event hardware durability

Hardware durability was assessed through measuring the percent of each training event that was recorded by the vehicular tracking systems. Any loss of data was attributed to hardware error (e.g., hardware breakage, power failure, data card fault, loss of hardware). Table 16 summarizes the total time recorded and total training time recorded for each event.

Table 16. Hardware durability performance by event (percentage of training time recorded).

Installation	Date	# Vehicles	Total Time (hr)	Recorded Time (hr)	% Recorded
Fort Riley	17-21 Aug 2009	18	1800.0	1489.1	82.7
Fort Riley	13-15 Jul 2010	7	332.6	250.9	77.8
Fort Riley	10-17-May2011	12	2108.2	1682.6	79.8
Fort Riley	17-22 May 2011	11	1515.9	1225.6	80.8
Fort Benning	18-20 Oct 2010	9	519.5	519.2	99.9
Fort Benning	28-29 Mar 2011	7	209.6	209.7	100.0
Fort Benning	31 Oct - 9 Nov 2011	20	4215.2	3998.6	94.9
Fort Benning	9-14 Nov 2011	22	2700.3	2700.3	100
PTA	6-9 Nov 2009	3	86.9	86.9	100
PTA	24-29 Jan 2010	6	509.9	471.8	92.5
PTA	17-23 Jan 2011	6	628.0	556.0	88.5
PTA	8-10 Jun 2011	2	49.2	49.2	100.0
PTA	13-14 Jun 2011	6	171.3	143.6	83.8
PTA	16-17 Jun 2011	7	220.2	2	92.5
TOTAL		139	15056.8	13587.1	90.2±2.3

A total of 13,587.1 hours of data were recorded out of 15,056.8 hours of total training time during which the units were mounted (90.2±2.5%). In addition, recorded time was analyzed by vehicle type to determine if hardware durability is a function of vehicle type (Table 17). Except for the HEMTT, over 80% of the data were recorded for each vehicle. Section 6.6 (p 82) contains a discussion on causes for greater hardware failure rates for the HEMTT vehicle.

5.6.4.1 Multiple live training event ease of use

A second objective of the multiple live training event demonstration phase was to assess the time requirements for implementing the VDMTS process. As described in Section 5.4.3 (p 54), the time required for training technicians on each step of the VDMTS as well as time required to perform each step were recorded. Table 18 documents the number of technicians trained for each step and the training time required for each step. Table 19 exhibits the time required to perform each step of the VDMTS process and summarizes the number of vehicles and events for which these data were collected.

Table 17. Hardware durability performance by vehicle type (percentage of training time recorded).

Vehicle	Type	Number Vehicles	Total Time (hr)	Recorded Time (hr)	% Recorded
HMMWV	Wheeled	59	8085.6	7597.9	93.9±2.9
MTV	Wheeled	7	649.4	550.5	84.8±11.3
Buffalo	Wheeled	1	71.9	71.9	100.0±0.0
Stryker	Wheeled	18	1785.2	1785.2	99.98±0.0
Bradley	Tracked	6	289.7	289.7	100.0±0.0
AAV	Tracked	26	1578.6	1424.2	90.2±4.6
Abrams	Tracked	1	30.1	30.1	100±0.0
HEMTT	Wheeled	12	1881.4	1181.2	62.79±13.9
LMTV	Wheeled	4	626.4	626.4	100.0±0.0

Table 18. Training times for each step of VDMTS implementation for ease of use assessment.

Parameter	Ease of Use - Training Times		
	Hardware Use	Data QA/QC	Analysis
# Technicians Trained	16	6	6
Average Time (hr)	0.3	1.07	6.33
Standard Deviation (hr)	0.12	0.11	0.82
Standard Error (hr)	0.23	0.35	2.58

Table 19. Performance times for each step of VDMTS implementation for ease of use assessment.

Parameter	Ease of Use - Performance Times		
	Equipment Setup/Removal (hr/vehicle)	Data QA/QC (hr/vehicle file)	Analysis (hr/event)
# Vehicles	136	136	136
# Events	14	14	14
Average Time (hr)	0.19	0.82	5.45
Standard Deviation (hr)	0.11	0.24	3.57
Standard Error (hr)	0.01	0.02	0.95

6 Performance Assessment

6.1 Controlled field study—Accurate VDMTS hardware measurement

The first component of the controlled field study demonstration plan was to validate the hardware function for recording vehicle dynamic and static properties for use in subsequent tests. Tests conducted included location, velocity, turning radius, and GPS signal loss (forcing INS system performance). The hardware system tests were conducted at the University of Tennessee. Results are applicable to all demonstration sites (Fort Riley, Fort Benning, Eglin AFB, and PTA).

The success criteria assigned to the position evaluation test was vehicle positional accuracy within 5.0 m (15.4 ft) 95% of the time. In the initial test, the VDMTS system was the worst performing of the five systems tested. However, after upgrading the VDMTS units to a differentially corrected GPS sensor, the system met the success criteria. The 6-hour static positional test for the upgraded unit resulted in an average error of 2.05 m with 99.87% of the data points within 5.0 m of the actual location exceeding the success criteria established.

A velocity evaluation test was performed on the VDMTS system. The success criteria assigned to this test was vehicle velocity within 2.24 m/s (5 mph) 95% of the time. The VDMTS calculated velocity was compared to the actual velocity. Three tests were performed and the VDMTS was well within the criteria at all times. The velocity evaluation resulted in a velocity within 2.24 m/s (5 mph) of the true value for 100 % of the data points.

The success criteria for the turning radius evaluation test was turning radius within 10 m 95% of the time. This criterion was measured by mounting the units on a cart pushed at two velocities on the track with a range of known turning radii. (Table 6 (p 55) lists the results. While the VDMTS did not predict the turning radius within 10 m for 95% of the time at both velocities, it was within 10 m for 95% of the test with the high accuracy, high-cost system (the best prediction available). It is interesting to note that the unit was more accurate at predicting small lower turning radii (sharper turns). Since vehicle impacts increase with decreasing turning radii, the VDMTS unit should allow for accurate impact prediction. Even though

turning radius prediction errors increased with increasing turning radii, the associated impact prediction error is small since lower impacts are observed in these conditions. Although the VDMTS hardware did not explicitly meet the success criteria established, it performed as well as alternative high accuracy systems indicating metric success.

The final success criteria for the first performance objective was to determine the ability to record in situations when GPS signals were not available due to topography, vegetation, and related conditions. This was tested by driving the unit through a tunnel and under heavy vegetation cover. Results show that the INS data collected from the VDM hardware increased the accuracy when compared to systems without INS capability. This is also illustrated when a GPS signal was not obtained in a field test at Fort Riley (Figure 27, p 73). The VDMTS met performance Metric 1.1, "VDMTS hardware with INS provides more accurate dynamic vehicle properties than GPS alone."

6.2 Controlled field study—Accurate VDMTS impact model predictions

The controlled field study demonstration plan assessed the impact models' accuracy of predicting site impacts based on vehicle dynamic properties. Tests conducted included DW, vegetation loss, and RD measurements. Impact models were validated under controlled conditions and during live training events at Fort Riley, Eglin AFB, and PTA.

The success criteria assigned to the model validation phase of the demonstration for DW is a correlation between predicted and measured values of 0.8 or higher and 95% of the predicted values are within 20 cm of the actual value. For vegetation loss (IS), the success criteria were a correlation between predicted and measured values of 0.7 or higher and at least 95% of the values within 20% vegetation removal accuracy. The criteria set for RD accuracy were a correlation greater than 0.6 and 95% of the points within 3.0 cm of the observed rut depths.

Table 20 summarizes the results from the controlled study at each location. The success metric was generally met for correlation between predicted and measured values for DW and vegetation loss. For DW, only 50% of the samples were within the 20 cm threshold. The theoretical vegetation loss (IS) model met the success criteria established. While the RD model met the percent samples within defined metric, it did not meet the correlation between predicted and measured metric.

When analyzing the data, it became apparent that the amount of variability experienced in measuring impacts was underestimated when establishing the metrics. In a validation project, metrics are established to compare results against some value to determine success or failure. In this case, somewhat arbitrary metrics had been established based on some previous data collected. Perhaps a better estimation of the theoretical model validity is comparing against an existing method of predicting impacts. Prior to the development of the theoretical models, a statistical regression model could be developed for a specific site/vehicle combination based on a field study similar to the controlled study. This empirical model could be considered the best prediction of impacts given the variability experienced in the field.

As a secondary measure of theoretical model success, statistical regression models were developed for each site/vehicle combination. Results from these models were compared with the same success criteria established for the theoretical models. (Table 20 also documents the results.) It is important to note that these results is biased towards the statistical models since they were developed using the same dataset used for the metric evaluation. The statistical DW model slightly outperforms the theoretical model; however it is not close to meeting the metrics established (Table 20). In fact, the theoretical model actually outperforms the statistical model in nearly every measure. For RD, it is apparent that the Fort Riley study did not result in a large range of rut depths. While the model predictions were very close to the observed measurements, the correlation between these two values was very low.

The data in Tables 20 and 21 indicate that the theoretical model performance was very comparable to the statistical models. When taking into account that this is biased towards the statistical model and the theoretical models can be used across different locations and vehicles, the value of the theoretical model is apparent. For this comparison, a separate statistical model was developed for each site/vehicle combination. In previous impact assessment work, this was required. However, a single theoretical model can be used across different locations and obtain results comparable to the multiple statistical models.

Table 20. Metric Analysis summary for theoretical and statistical models in Fort Riley, Eglin AFB, and PTA Controlled Study (Note: Units are cm for DW, RD and percentage for IS).

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Correlation between predicted and measured	0.89	0.94	0.90	0.90	0.1	0.5
Average error between predicted and measured	-0.2 cm	2.7 cm	-1.3%	1.7%	0.5 cm	-1.4 cm
Average absolute error between predicted and measured	28.0 cm	18.8 cm	10.8%	9.7%	0.6 cm	1.8 cm
% Samples within defined metric	50%	67%	86%	78%	94%	85%

Table 21. Average absolute error between predicted and measured values for theoretical and statistical models from controlled study (Note: Units are cm for DW, RD and percentage for IS).

	Riley			Eglin AFB			PTA			Combined		
	DW	IS	RD	DW	IS	RD	DW	IS	RD	DW	IS	RD
Theoretical	22.0	9.8	1.1	33.9	9.8	0.1	22.4	13.4	0.7	28.0	10.8	0.6
Statistical	13.0	11.5	3.9	24.2	7.5	0.9	14.8	10.8	1.0	18.8	9.7	1.8

Table 8 (p 63) lists the results from the controlled study model validation at Fort Riley. The theoretical model predictions met some of the predefined success criteria while not meeting others. However, essentially the same outcome was observed for the statistical models. When creating the metrics and success criteria, the variability of experience in the field was underestimated. This is evidenced by the fact that the site-specific statistical models did not even meet the success criteria. In summary, even though the theoretical models did not meet the success criteria established, their validity was confirmed since they produced similar results to the statistical models. While theoretical models did not meet all of the metrics established, their performance was validated when compared with previous method results.

6.3 Single live training event—Accurate VDMTS hardware measurements

Single live training events were tracked at Fort Riley and Fort Benning. A total of 38 vehicles were tracked across those two events representing four vehicle types. The positional accuracy met the metric criteria with an off-road positional accuracy observed of 1.6 m (± 0.1 m).

At several instances during the live training event at Fort Riley, the GPS signal was lost. In these cases, the VDMTS INS system succeeded in calculating vehicle location. Figure 27 (p 73) shows one instance where the GPS lost reception and INS calculated the vehicle location. In this instance, the GPS signal was lost for over 700 m (2296 ft).

To assess INS performance, data were analyzed on a subset of the vehicle files with and without the GPS data (48259 samples). The success criteria for this metric was vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal was lost 90% of time. In the subset of 10 vehicles, the positional accuracy never exceeded the 10 m threshold signifying the success criteria were met. The average error compared with the GPS signal was 0.164±0.002 m. Across the 48259 samples, the maximum error compared with the GPS signal was 2.60 m.

6.4 Single live training event—Accurate VDMTS impact model predictions

One component of the single live training event study at Fort Riley and Fort Benning was to test the predictions of the theoretical impact models in field conditions. This study compared model predicted impacts with measured impacts from the same event. The success criteria established for this test was predicted DW within 20 cm of actual disturbed width in 90% of the sample sites, predicted vegetation loss within 20% of actual vegetation loss in 80% of the sample sites, and predicted RD within 4 cm of actual rut depth in 80% of the sample sites. As discussed in Section 5.6.3 (p 69), the predictions from the statistical regression models were also compared against the success metrics to estimate the accuracy of the theoretical models compared to the previous method of predicting impacts. Tables 22–24 summarize the data against these metrics.

Table 22. Summary of single live training event tracking at Fort Riley.

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Average error between predicted and measured	2.9 cm	–21.4 cm	–3.3%	–12.3%	0.1 cm	–0.2 cm
Average absolute error between predicted and measured	24.8 cm	27.2 cm	7.7%	12.9%	0.7 cm	0.9 cm
% Samples within defined metric	48.8%	52.4%	93.9%	82.9%	98%	100%

Table 23. Summary of single live training event tracking at Fort Benning, GA.

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Average error between predicted and measured	27.6 cm	9.8 cm	−0.2%	5.9%	0.0 cm	−0.5 cm
Average absolute error between predicted and measured	34.8 cm	32.6 cm	4.9%	6.4%	0.0 cm	0.5 cm
% Samples within defined metric	42.3%	47.4%	96.2%	98.7%	100%	100%

Table 24. Summary of single live training event tracking at Fort Riley, KS and Fort Benning, GA (combined).

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Average error between predicted and measured	14.9 cm	−6.1 cm	−1.8%	−1.7%	0.1 cm	−0.2 cm
Average absolute error between predicted and measured	29.7 cm	29.8 cm	6.3%	8.3%	0.7 cm	0.9 cm
% Samples within defined metric	45.6%	50.6%	95.0%	93.1%	98%	100%

The metrics established for vegetation loss and RD were met (vegetation loss within 20% and rut depth within 4 cm of the actual values for at least 80% of the sampling sites) while the metric established for DW did not meet the established metric (< 90% of the data within 20 cm of actual disturbed width). However, the average absolute error between the predicted and measured values for DW was the same when predicted with the theoretical model and the site and vehicle-specific statistical model (29.7 cm vs. 29.8 cm). While the statistical models performed better than the theoretical models in the controlled study, the theoretical models performance was similar to the statistical models in the live single training event study. In fact, the theoretical model performed better than the site and vehicle-specific statistical model in predicting vegetation loss. Previously, a separate study was required to develop a statistical model for each site being tested resulting in added study costs. The theoretical model removes this necessity while providing an estimate of the training event impacts.

6.5 Single live training event—VDMTS hardware durability

The last component of the single live training events was to assess hardware durability. The success metric established for this study was percent of recorded time > 80% of the actual military training time. Hardware durability in single events was assessed at Fort Riley, Fort Benning, and PTA. The data in Table 15 (p 72) indicate that this metric was met at all three locations with a total of 85.5% data recorded across the three events.

6.6 Live training—VDMTS hardware durability

The hardware durability described in the previous section was also assessed across all of the training events in the last phase of the demonstration. For this assessment, the success criteria established was percent of recorded time >80% of training time per vehicle type for any event. The success metric was changed to investigate durability by vehicle type to determine if hardware durability was independent of the vehicles being tracked.

This demonstration tracked 14 training events at three locations, totaling 136 vehicles tracked. The demonstration resulted in 13587.1 hours logged out of 15056.8 total hours of training resulting in VDMTS units recording 90.2% (±2.3%) of the total training events tracked. In every event but two, >80% of the data were collected (77.8% and 79.8% on 13-15 July 2010 and 10-17 May 2011, respectively). Separating the data by vehicle type, >80% of the data were collected except for the HEMTT vehicle (62.8 ±6.9%). The reason more data were lost on the HEMTT vehicles is unclear. This could be due to the mounting location available for the HEMTT. Often times, the only location available for mounting was on top of the spare tire behind the cab. It is possible that this mounting surface resulted in more vibration or movement of the units causing more data faults. The lower recording rates in the HEMTT vehicle does explain the low collection rate on the 10-17 May 2011 event as half of the vehicles being tested were HEMTTs. Another explanation for low collection rates for the HEMTT vehicles is that older units were often used on the HEMTT vehicles. Troops suggested that that these vehicles were less likely to travel off-road. In an effort to collect as much off-road data as possible, newer units were mounted on vehicles more likely to travel off-road.

While the failure of data collection on the HEMTT is cause for some concern, the influence on the total off-road impacts is minor. In 14 training tracked events, very few HEMTTs were observed going off-road. A lesson learned from these demonstrations was that care should be taken to ensure the units are mounted as securely as possible, especially when mounting units on the HEMTT vehicles.

6.7 Live training—Quantitative ease of system use

The system ease of use was measured quantitatively by determining the time required to perform each task and compare with a time deemed acceptable in the approved demonstration plan. The success criteria were developed through discussion with installation staff and ESTCP management. In the demonstration plan, the success metric established for time required for analysis was 40 hours per five events at each installation. Since it was not possible to track five events at both installations, the success metric was modified to 8 hours per event to account. Tables 25 and 26 list the success metrics and times required for each task. In every case, the system met the success metrics established ($p < 0.05$). This indicates the system was simple enough for easy implementation into the management program without extensive training or time requirements.

Table 25. Training summary for ease of system use assessment.

	Hardware Use (hr/person)	Data QA/QC (hr/person)	Analysis (hr/person)
Success Criteria (H_0)	4.0	4.0	16.0
Average Time (hr)	0.3	1.07	6.33
Standard Error (hr)	0.23	0.35	2.58
T-test (average time <success criteria)	p < 0.0001	p < 0.0001	p < 0.0001

Table 26. Summary of time requirement to perform each step in the VDMTS process.

	Equipment Setup/Removal (hr/vehicle)	Data QA/QC (hr/Vehicle File)	Analysis (hr/Event)
Success Criteria (H_0)	1.0	1.0	8.0
Average Time (hr)	0.19	0.82	5.45
Standard Error (hr)	0.01	0.02	0.95
T-test (average time <success criteria)	p < 0.0001	p < 0.0001	p = 0.00958

6.8 Live training—Quantitative quality and accuracy of data

This performance objective was designed to test the hardware and model components ability to produce actionable results for installation land managers. This objective had two components. First, to determine if the data quality was sufficient for use as inputs in models (e.g., Fort Riley nLS model, ATTACC) used in land-use decision making. Secondly, it was designed to determine if the data quality was sufficient to identify training area use patterns. Identifying training area use patterns assists installation land managers in identifying the following: LRAM sites, low water crossing usage, emerging trails, and impact to TES habitats (e.g., RCW and Gopher Tortoise). The data requirements and the associated success criteria for each objective were developed through consultation with installation land managers (e.g., ITAM and Environmental) as well as regulation authorities (e.g., USFWS).

The first metric objective was to assess the ability to use the data for parameterization of land management models. The resolution of each specific model defines the acceptable accuracy of data for model parameterization. If the demonstrated accuracy was greater than the model resolution, the data quality is sufficient for model parameterization. The data types also varied with the input requirements of the model of interest. In the approved demonstration plan, it was proposed these data be used for parameterization of a Kinematic Wave model used at Fort Riley (nLS model) to predict erosion and gully formation. It was also proposed to use the data to determine better estimates of Vehicle Off-Road Factor, Vehicle Severity Factor, and Vehicle Conversion Factor for use in ATTACC methodology. As described in Metric 8.1 in Section 3.8.1 (p 32), a success criterion of < 10 m positional error is established. Success criteria for time off-road, vegetation loss, and IS are errors less than 20%. Section 3.8 describes the methods for obtaining these criteria.

The observed accuracy in this demonstration for each data type are 1.6 m average positional error, 1% error in estimating time off-road and 6.3% error predicting IS. These measured accuracies meet the proposed success criteria for each data type. These values also allow determination of the ability to use this system to parameterize different models. If the model requires vehicle-tracking data and uses a spatial resolution of 3 m, the accuracy of this data for model use is adequate. However, if an erosion prediction model required 5% accuracy of vegetation cover for acceptable re-

sults, data quality from the VDMTS process (hardware and models) is not high enough for implementation in the model.

The second metric objective was to determine if VDMTS data quality is sufficient to identify training area use patterns. Vehicle positional accuracy is required for training use pattern identification. Some pattern identification (i.e., LRAM site identification) requires vegetation loss predictions. Knowledge of training relative to known TES habitat locations also requires vehicle positional data. Vehicle positional accuracy required for LRAM and other maintenance requirements was determined to be < 10 m positional error. For TES habitat impact analysis, a < 5 m positional error is required. Additionally, < 20% error in vegetation removal is needed for site maintenance requirements. Metric 8.2 in Section 3.8.2 (p 34) documents the development of these success criteria.

The observed accuracy in this demonstration for each data type is 1.6 m average positional error and 6.3% error in vegetation loss estimation. These measured accuracies meet the proposed success criteria for each data type. Again, this approach can be taken to determine if data quality is acceptable for any training area use pattern quantification and analysis.

6.9 Live training—Qualitative ease of system use

In addition to quantitative ease of use metrics, a qualitative ease of use metric was proposed in the demonstration plans. This was aimed at determining if the effort required to training a technician in VDMTS operation and performance of tracking events and data analyses was acceptable. The qualitative metric was also proposed to obtaining any feedback from the installation technicians on use of the systems to identify any drawbacks to the system and learn from any suggestions they may have.

To test this metric, each technician who used the system in the demonstration was given an evaluation form (Appendix D). Technicians only filled in the evaluation sections relating to their experience with the system. For each step of the data collection, they were asked to give a 1-10 rating (where 10 indicates no issues with that step, and 1 indicates an unusable/difficult step). To supplement the small sample of technicians, additional students from the University of Illinois and University of Tennessee (with B.S. and M.S. backgrounds in similar fields of study as military installation technicians) were trained and asked to evaluate the system and training. Table 27 lists the results of these evaluations. An average rating >7 indicates no major issues with that step in the VDMTS process.

Table 27. Summary of evaluation forms received from technicians on VDMTS use.

Task	Average Rating	Comments
Operation of vehicle-tracking hardware	9.3	Overall, VDM boxes were fairly easy to use. There were problems w/the magnetic mounting of the GPS sensor.
Mounting and dismounting of hardware	8.7	There were some issues mounting boxes to vehicles (i.e., finding secure place to mount without getting in way). Hardware needs to be places securely and oriented correctly.
Hardware maintenance (e.g., charging/replacing batteries, data card replacement, etc.)	9.5	The new units were easier to charge than older models (pre-demonstration); however it would be nice to have better access to the data card.
Downloading data	10	
Checking data on computer for errors and completeness	8.5	
Processing raw data files	7	The process is straightforward and simple, but takes time to complete if there are many vehicles.
Processing data to determine vehicle velocity and turning radius	8	
Using vehicle impact models for prediction of impacts	7	
Analyzing impact data for site-specific summaries	8	

In addition to the questions related to specific tasks, the installation staff members were asked if they had any additional comments regarding system use. One PTA staff member responded:

> I really love the new tracking units. They are so easy to work with. We had them inside the turret with the antenna stuck on the top of the vehicle. I hope this worked out well and the data is meaningful. Vehicle R-7 is a wrecker. That went out on the maneuver training exercise. I would like to track the damage caused by that vehicle as it weighs another 10,000 lbs I believe. I wrote the weight down on one of those sheets. What do the new units cost to put together? Can I get the parts to make my own here in Hawaii? Can you put together a parts and price list so that I can start to do this.

The qualitative metric was a good way to document feedback from installation staff that may otherwise be lost. Overall, the results of the qualitative ease of use metric indicated that vehicle-tracking units were easy enough for the technicians to work with. There were a few comments and concerns

that can be addressed in the systems in the future. Since the VDM units are a custom-built product, it is possible to request certain component changes if an installation requests.

6.10 Live training—Qualitative quality and accuracy of data

A similar qualitative metric was proposed to assess quality and accuracy of data for land-use decision making. This metric was proposed to document issues and comments installation technicians had regarding implementing the VDMTS process in their programs. Similar to the previous section, an evaluation form was given to each technician who used the system in the demonstration. (Appendix D includes the form.). Technicians only filled in the evaluation sections relating to their experience with the system. Table 28 summarizes the responses received in these evaluation forms.

Installation staff members were also asked if they had any additional comments regarding implementation of the system into their program. Fort Benning staff provided the following comment:

> We really appreciate the support from ERDC/CERL and the University of Tenn. in executing this project on the ground so quickly. This monitoring support was instrumental in gaining the confidence and approval of the USFWS in addressing increased vehicular traffic related concerns around RCW clusters that were addressed in a biological evaluation of effects for changes to the Program of Instruction (POI) for the ARC. Additionally, subsequent vehicular tracking events will augment an existing research project (Heavy Maneuver Effects on RCWs) which was a term and condition of the jeopardy biological opinion for BRAC/MCoE actions at the Installation. Thanks, Tim Marston, Lead Wildlife Biologist - RCW, Ft. Benning, GA.

Figures 28 and 29 show examples of data analyzed to provide Fort Benning quantitative data for training time near RCW clusters. The distance thresholds represent distances with known military training impacts to RCWs.

Table 28. Summary of evaluation forms received from installation land managers on use of data collected with the VDMTS.

Issue	Average Rating	Comments
Data collected are of value for decision making	9.3	This will be very useful data for assessing impacts of heavy maneuver effects on RCWs pertaining to the Army Reconnaissance Course (ARC) when providing briefings to the USFWS and our chain of command.
Maps produced from data aid in visualization and analysis of vehicle use patterns and associated impacts	9	This will be very useful data for assessing impacts of heavy maneuver effects on RCWs pertaining to the ARC when providing briefings to the USFWS and our chain of command.

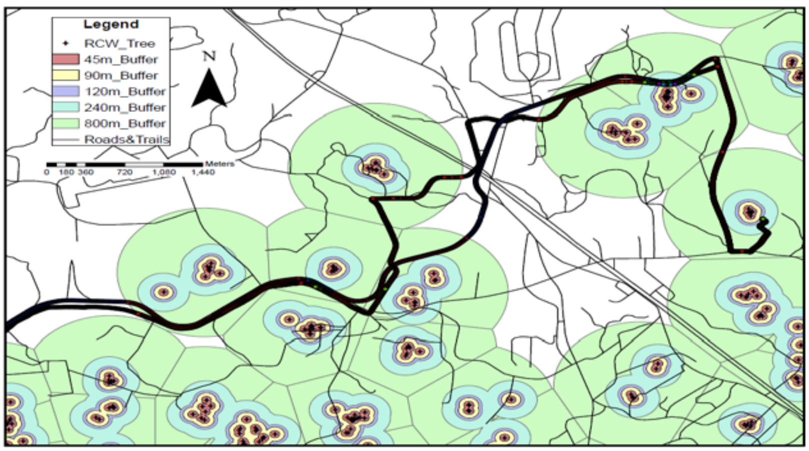


Figure 28. Training distance from RCW clusters.

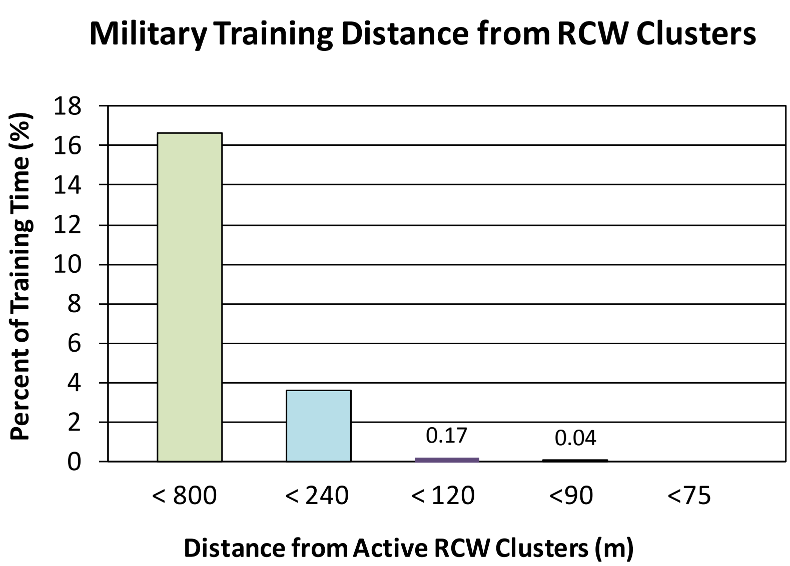


Figure 29. Percent of training time within certain distances of RCW clusters.

Fort Riley technicians expressed interest in incorporating data collected from this demonstration plan with the nLS Gully Formation Prediction Model (ESTCP Project RC 200820), and voiced their excitement to learn that this was already underway. Additionally at both Fort Riley and PTA, implementation of the VDMTS process was incorporated into the proposed ITAM 5-year plans.

Overall, while this demonstration project dealt with issues relating to the ability of tracking off-road military training exercises, at every location land managers expressed their eagerness to use the systems, and indicated that they could see how the data collected was beneficial to their needs after seeing the process. It is also interesting to note that each land manager indicated that they could see how the data fit into their programs in different ways (i.e., gross estimation of expected impacts and trail development at PTA (Figures 30 and 31), data collection for predictive models and ID of LRAM locations at Fort Riley (Figure 32), and quantification of training maneuver patterns related to RCW nesting trees at Fort Benning (Figures 28 and 29). As such, this project met the qualitative quality and accuracy of data metric.

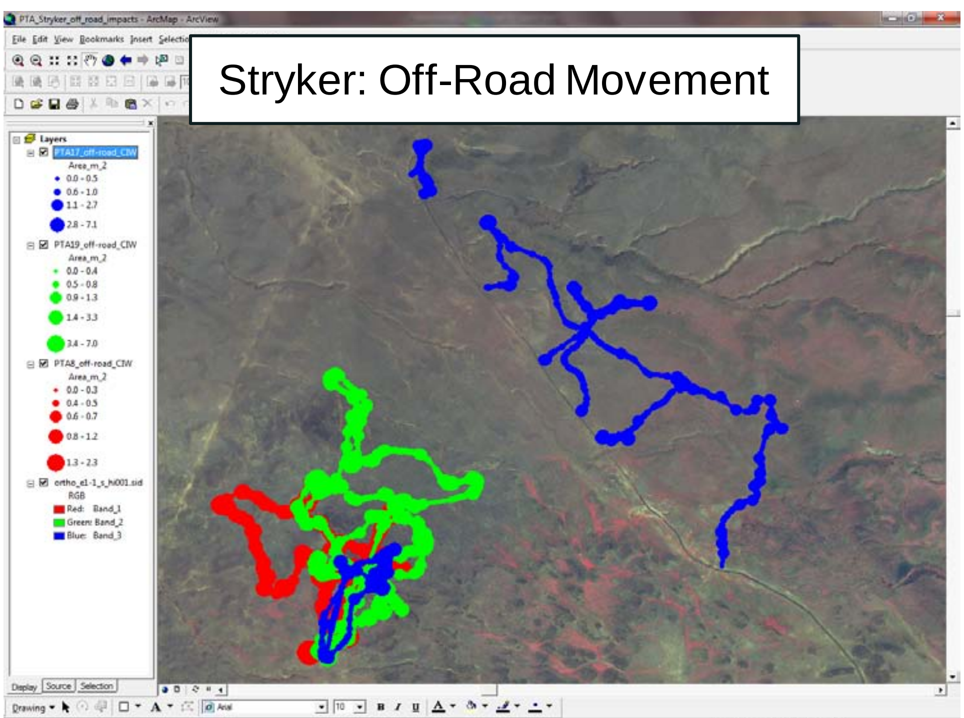


Figure 30. Off-road training at PTA. Each color (red, green, and blue) represents an individual Stryker vehicle. Thicker lines represent higher DW and vegetation removal at those points.

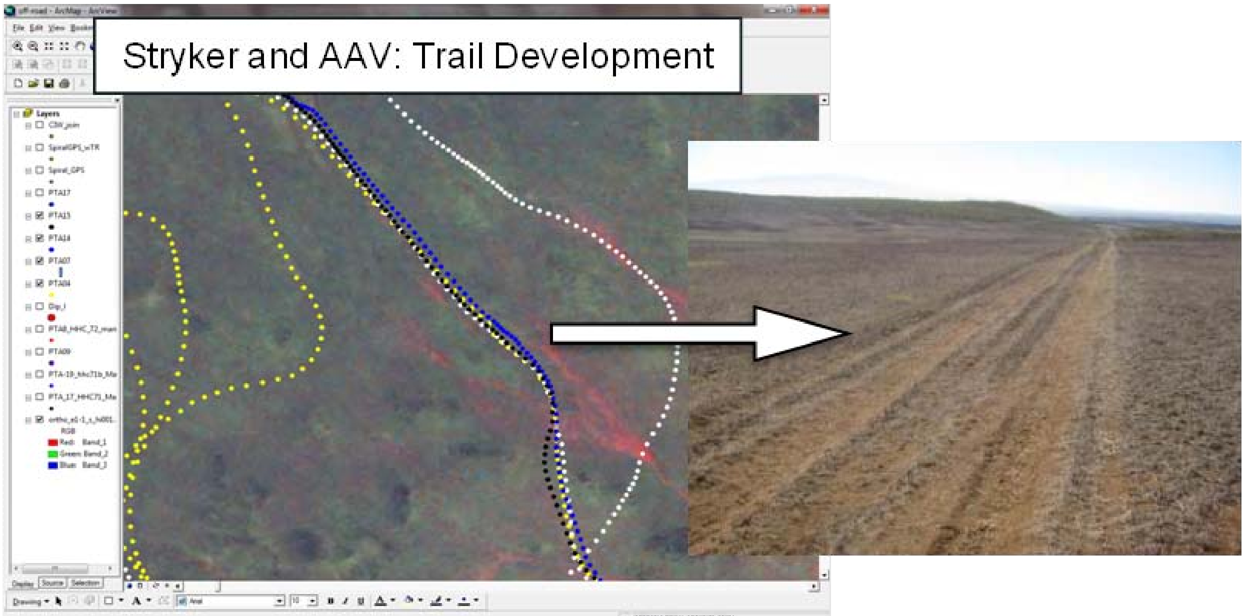


Figure 31. Identification of potential areas for trail hardening at newly opened training area at PTA. Data from multiple training events were overlaid to identify key areas trail development. Different colors in the map represent individual vehicle tracks.

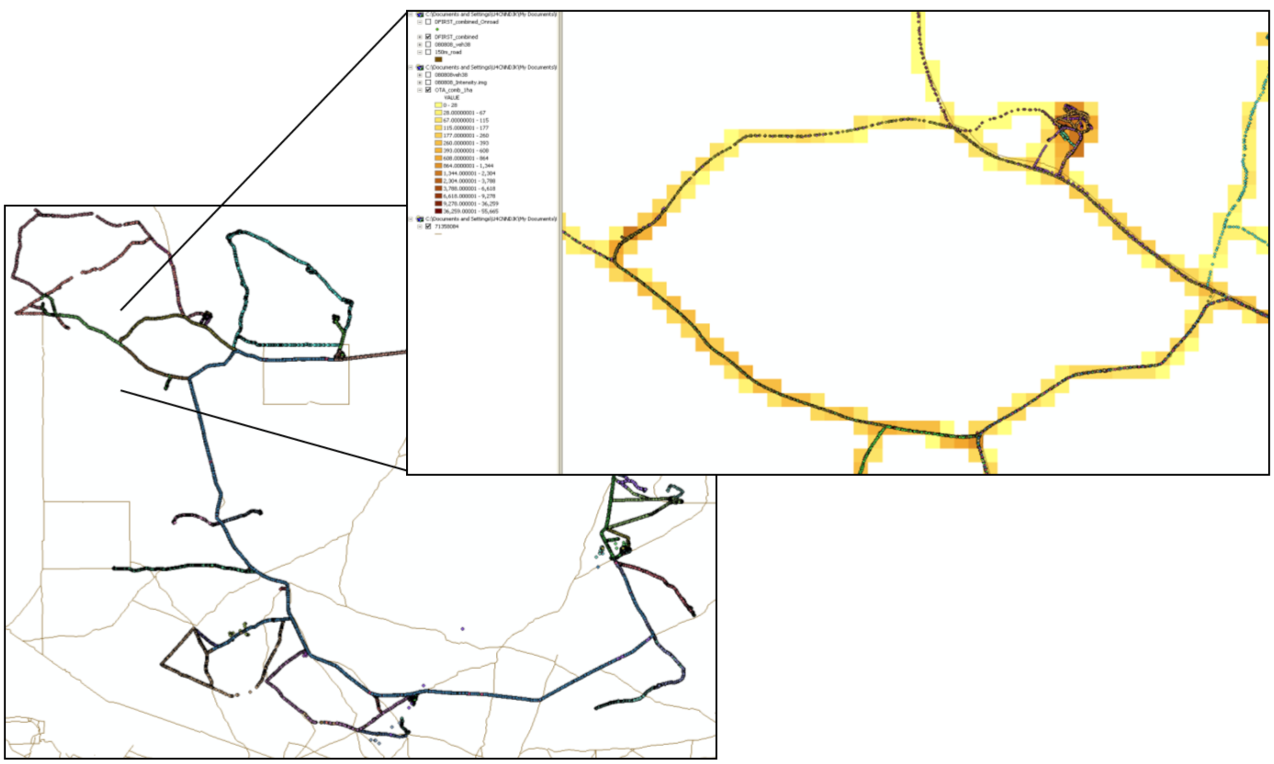


Figure 32. Example of training intensity map developed from VDMTS process. Darker colors indicate more time spent in those grid cells.

7 Cost Assessment

A main objective of this demonstration was to provide accurate estimates of VDMTS implementation costs and estimated savings in land management costs.

7.1 Cost model

Since there is no existing technology to compare costs, several other technology cost implementation scenarios were evaluated. Hardware purchase and replacement costs are most easily summarized in "cost per event tracked." Data analysis costs are generally based on a "cost per question asked" since the question could require multiple events be tracked or could reuse previously collected data.

To resolve the issue of VDMTS lifecycle costs existing in different units (cost per event, cost per question) costs were estimated for several implementation scenarios. The scenarios were intended to show that costs vary between installations that want to track many events to those interested in tracking only a few. The scenarios illustrate costs associated with different fielding strategies, from those that rely on individual installations for implementation to those that rely on regional or national support centers. Note that the following scenario descriptions are hypothetical. Table 30 lists the cost development approach for the scenarios, which were derived from interviews with installation personnel:

1. *Scenario 1*. An installation that needs to track several events to answer one management question, and that never intend to use the technology again. This scenario is representative of an installation needing to track military vehicles to assist with an EIS or biological assessment. This scenario would track 20 vehicles for 5, 1-week long events over a period of 1 year.
2. *Scenario 2*. An installation that needs to continually track a certain number of events each year for an indefinite period of time. This scenario is representative of an installation needing to track military vehicles to show compliance with an established policy or agreement. This scenario would track 20 vehicles for 10, 1-week long events every year for 5 years.
3. *Scenario 3*. An Army regional support center provides support to all installations requiring use of VDMTS services. This could also be a contractor that provides vehicle-tracking support to installations under contract. This

scenario is representative of an implementation decision to support multiple installations more economically. This scenario is based on the US Army Sustainable Range Program installation support model. This scenario would potentially include 10 installations that each need to track 20 vehicles for 10, 1-week long events every year for 5 years.

4. *Scenario 4*. Official Army weapon and training system data (e.g., DFIRST, BFT) become available to provide vehicle static and dynamic property information. For this cost analysis, it was assumed that the Army users (e.g., ITAM and Environmental) would have access to these data. Therefore, only data analysis costs and possibly some limited data acquisition costs are required. Currently however, this assumption likely does not hold true and acquisition costs (time and money) would be higher than assumed. This scenario used the same installation requirements as Scenario 2 for comparison (20 vehicles for 10, 1-week long events every year for 5 years).

Table 29 summarizes estimates for the cost elements. Cost elements are the main cost groups associated with technology use. Sub-element costs are a further breakdown of costs categories associated with a specific cost element. The intent of this table is to identify all data and information that were tracked through demonstration implementation. These data were used to calculate costs for each scenario (Table 30).

7.2 Cost drivers

The cost drivers for implementing the VDMTS process and determining which application and technology is most cost effective are highly dependent on the specific situation at each installation and the issues being addressed. For example, it is anticipated that larger installations with more personnel would be able to implement the VDMTS process in-house. In contrast, a small branch (only a few people) at a smaller installation may need to hire a regional support center to perform the analyses needed. Additionally, the cost for implementing the system depends on the issues being addressed and the data needed to answer those questions. An installation needing to track only a few events could hire a regional support center to perform the analysis required. It may be more cost effective, however, for the installation to implement the system in-house if many training events were to be monitored over a long period of time (5 years). The following section expands on these anticipated cost drivers and provides recommendations for system implementation given different scenarios.

Table 29. Cost model.

Cost Element	Cost Sub-element	Data Tracked
VDMTS hardware cost	Purchase	Initial hardware purchase cost reported as average cost per vehicle-tracking unit. Initial hardware cost data collected by Cybernet during system production.
	Maintenance/ replacement	Hardware maintenance/replacement cost takes into account life expectancy and maintenance costs. Life expectancy is estimated based on input from Cybernet Systems. Maintenance costs include part (e.g., battery, switches, etc.) replacement and repair. (Table 31 lists the estimation of maintenance/replacement cost.)
Training	Hardware	Cost of labor for person to learn how to operate and maintain hardware. Cost is based on number on hours of training per person trained and average employee cost/hour. Cost data were collected during single and multiple tracking event activities.
	Data processing	Cost of labor for person to learn data processing and data QA/QC procedures. Cost is based on number of hours of training per person trained and average employee cost/hour. Cost data were collected during single and multiple tracking event activities.
	Data analysis	Cost of labor for person to learn data analysis procedures. Cost is based on number of hours of training per person trained and average employee cost/hour. Cost data were collected during single and multiple tracking event activities.
Event tracking Event tracking	Preparation	Labor cost to maintain and prepare systems for event tracking. Includes battery recharging, minor repairs, and system performance checks. Cost based on average time per tracking unit and average employee cost/hour.
	VDMTS setup	Labor cost to install systems in the field. Cost based on average time per tracking unit and average employee cost/hour. Data collected during single and multiple tracking event activities. Generally, these costs are cost per event tracked.
	VDMTS removal	Labor cost to remove systems in the field. Cost based on average time per tracking unit and average employee cost/hour. Data collected during single and multiple tracking event activities. Generally, these costs are cost per event tracked.
	Data processing	Labor cost to download, perform quality control, and pre-process data. Cost based on average labor time for QA/QC preprocessing per tracking unit per event multiplied by average labor cost. Data collected during single and multiple tracking event activities. Generally, these costs are cost per vehicle tracked.
	Travel	Travel cost associated with event tracking. This cost includes airfare/rental car and per diem. This cost is estimated since travel costs vary depending on distance and location. This cost is necessary to accurately assess the different implementation scenarios.
Event analysis	Basic summary	Cost to perform basic analysis of vehicle-tracking data. This includes performing impact assessment analysis of the vehicle-tracking data with the theoretical models, incorporating data into GIS environment, and performing basic event summaries. Cost based on average labor time for basic vehicle impact summarization. Generally, these costs are cost per vehicle tracked. Data collected during single and multiple tracking event activities.
	Site/question-specific summary	Data interpretation/summarization to meet land management objective. This could be the percent of vegetation removal by location, percent time off-road, or amount of time vehicles spent in TES habitat. Cost based on average labor time for data interpretation/presentation for land management problem. Cost is the total personnel labor multiplied by the average labor cost. This cost is likely to be more variable than other costs depending on the question asked. Data collected during single and multiple tracking event activities.

Table 30. Cost model for alternative fielding scenarios.

Cost Element	Cost Sub-Element	Costing Analysis Scenario: Installation Performed (Scenarios 1 and 2)	Regional Support Center (Scenario 3)	Army Standard System (DFIRST/BFT) (Scenario 4)
Hardware	Purchase	$2900/unit	$2900/unit	NA
	Maintenance/replacement	$32/unit/event	$32/unit/event	NA
Training	Hardware	4 hr/class * $37/hr	4 hr/class * $37/hr	NA
	Data processing	4 hr/class * $37/hr	4 hr/class * $37/hr	4 hr/class * $37/hr
	Data analysis	16 hr/class * $53/hr	16 hr/class * $53/hr	16 hr/class * $53/hr
Event tracking	Preparation	0.5 hr/unit * $37/hr	0.5 hr/unit * $37/hr	0.0 hr/unit
	Setup	0.3 hr/unit * $37/hr	0.3 hr/unit * $37/hr	0.0 hr/unit
	Removal	0.1 hr/unit * $37/hr	0.1 hr/unit * $37/hr	0.0 hr/unit
	Data processing	1.0 hr/unit * $37/hr	1.0 hr/unit * $37/hr	1.0 hr/unit * $37/hr
	Travel	$0/event	$1500/event	$0/event
Event Analysis	Basic summary	1.0 hr/vehicle * $53/hr	1.0 hr/vehicle * $53/hr	1.0 hr/vehicle * $53/hr
	Site-specific summary	8.0 hr/summary * $53/hr	8.0 hr/summary * $53/hr	8.0hr/summary * $53/hr
Total Costs	Purchase costs	$2900/unit	$2900/unit	$0
	Training costs/individual	$1144/individual	$1144/individual	$996/individual
	Fixed cost/event	$499/event	$1999/event	$424/event
	Cost/vehicle tracked/event	$123/vehicle	$123/vehicle	$90/vehicle
	Cost for proposed scenarios	Scenario 1: $76,954 ($76,954/yr/site) ($15,391 event) Scenario 2: $237,244 ($47,449/yr/site) ($4,745/event)	$2,649,288 ($53,185/yr/site) ($5,299/event)	$112,196 ($22,439/yr/site) ($2,244/event)

* BFT = Blue Force Tracker
DFIRST = Deployable Force-on-Force Instrumented Range System

7.3 Cost analysis and comparison

7.3.1 Monitoring methods and costs

A cost analysis was performed for the scenarios defined in Section 7.1 (p 91) using the data collected (Table 29). The cost data listed in Table 29 were collected throughout the demonstration from a number of sources. Hardware costs were obtained from the suppliers (e.g., Cybernet, parts suppliers, etc.). Hardware maintenance costs were calculated from the costs observed throughout the demonstration. Time requirements for each component were obtained through this demonstration (Performance Objective 7). The labor costs for technicians were obtained through discussions with installation managers (average labor costs per technician level) and from ITAM program.

The demonstration resulted in an average of 11 events tracked per VDM tracking unit. Throughout the demonstration, no units failed to the point that they needed replacement (disregarding minor issues like battery replacement, switch replacement, etc.) This does not allow for an estimation of unit lifespan. Based on discussions with the unit manufacturer and based on observations throughout the demonstration, a unit lifespan of 100 events was estimated. This number was selected as a conservative estimate of the hardware's actual lifespan. The design of the hardware is a printed circuit board with all surface mount components. This design is very resistant to physical shock and vibration. The most susceptible points of failure are the SD Card connector, electrical power connections and switches, and GPS antenna, which are all easily replaced. The actual lifespan depends on the severity of the conditions the unit is being used in, the average length of deployment, and other factors.

Because the cost of implementation is highly dependent on the situation for which it is being used, an extensive life cycle cost analysis is difficult without making a number of assumptions. To estimate life cycle costs and yearly costs, the cost analysis approach taken is to assume the different scenarios described in Section 7.1 (p 91). A lifecycle cost analysis of the hardware was performed to estimate a maintenance/replacement cost per event (Table 31). The estimated maintenance/replacement cost per event was used in the scenario costing analysis (Table 30) to account for the cost per event to repair or replace each unit averaged over the estimated lifespan of the hardware.

Table 31. Lifecycle cost analysis of VDMTS hardware.

Lifecycle Cost Component	Cost/unit	Replacements Required/Lifespan	Cost/Lifespan
Initial purchase cost	$2,900.00	1	$2,900.00
Battery replacement	$36.86	2	$73.72
GPS antenna replacement	$31.00	1	$31.00
Switch replacement	$7.00	2	$14.00
Wiring and connections	$20.00	2	$40.00
Misc. Costs (data cards, card connectors, etc.)	$30.00	4	$120.00
Total replacement cost			$3,178.72
Estimated Unit Lifespan (# Events)			100
Maintenance-replacement cost per event per unit			$31.79

As shown in Figure 33, a regional support center does not actually reduce total costs to the Army using the given costs. This is due to the travel costs required for technicians to reach the site. The cost of $1500/event is based on airfare, hotel, and per diem for the week outweighs any benefit the regional support center gives from a reduction in equipment/labor needed per installation. If these travel costs are lower (e.g., due to proximity to installation), the slope of the Regional Support Center line (shown in Figure 33) is reduced and it can become less expensive for a regional support center to perform the studies. For example, if travel costs per event are reduced to $1000, it becomes more economical for a regional support center to implement the system as the number of installations becomes greater than 13.

This cost analysis is limited by the data collected through this demonstration. Since this demonstration only estimated a cost requirement to perform the VDMTS process, the relationship between cost and number of events (or installations) is a linear function. This assumption is accurate in the case of Scenario 1 and 2. As more installations adopt the VDMTS method under these scenarios, the total cost to the military increases linearly as the efforts are replicated for each installation. In the case of Scenario 3, as the number of events tracked increased, the cost per event would decrease due to economies of scale (e.g., increased efficiency of labor, decreased analyses times, etc.). However, the cost data collected in this demonstration do not allow for the determination of the decreasing costs per event collected for Scenario 3.

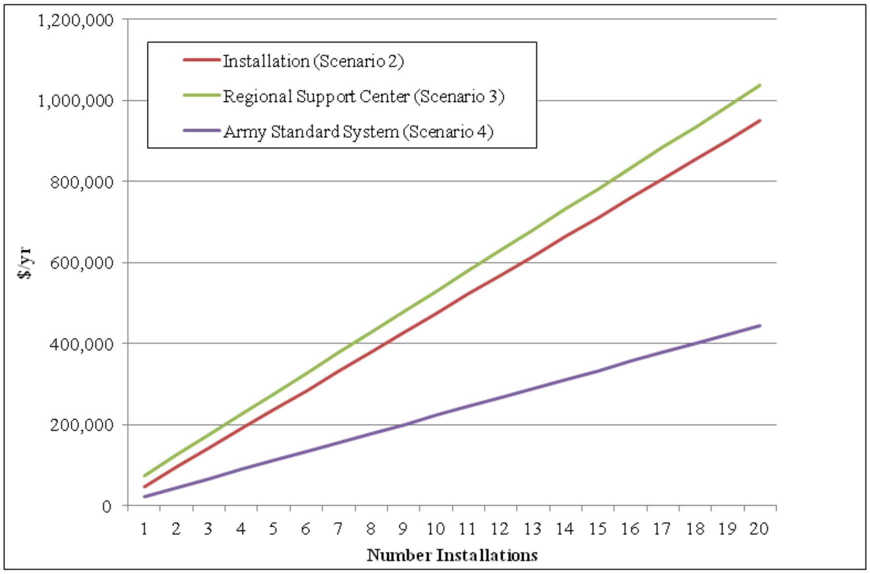


Figure 33. Total cost to Army from different scenarios with increasing number of installations adopting process (Assumes 10 events of 20 vehicles/event at each installation over 5 years at the costs given in Tbl. 3 [p 22]).

It is important to note that these cost analyses assume the installation (in the case of Scenarios 1 and 2) has adequate resources to support the system implementation. In the case of smaller installations, technicians may not be available or have the skill set required to perform the vehicle impact analyses. In these cases, it is more economical to use the support of a regional center to implement the VDMTS process.

7.3.2 Alternative monitoring methods and costs

Two alternative options to the VDMTS system were also identified through discussion with military land managers. However, the VDMTS process provides land managers with data and products that cannot be produced with either of these monitoring methods. This cost comparison can give an idea of VDMTS implementation costs compared with existing monitoring costs. However, calculating a lifecycle costs savings may not be as appropriate since the comparison involves different technologies and issues.

The two alternative options currently being employed at military installations to determine locations of vehicle training impacts and gauge the severity of these impacts are remote sensing and "windshield surveys." Fort Riley is currently implementing a land change detection model based on bi-monthly 250 m resolution Moderate Resolution Imaging Spectroradiometer (MODIS) data. According to the ITAM coordinator, this process now requires a GIS analysis approximately 2 hours every 16

days to update the dataset and perform the change detection analysis. Assuming a rate of $53/hr (Fringe rate for GS12 Step 3) that results in operating costs of $2418.13 per year. However, this product was recently developed and is currently only available at Fort Riley. As such, accurate cost data for implementation at other installations are not available for comparison to the VDMTS process.

The MODIS land change detection method allows for a quick, low-cost view of change detection over the entire installation. This data can be calibrated with bare ground and biomass data collected through field sampling. Fort Riley personnel expressed their desire to use both the high-quality, high-resolution data collected from the VDMTS system with the rapid, low-cost remote sensing change detection data collected through the MODIS land change detection model. Integration of the two systems would allow for timely, continuous land condition assessment and LRAM intervention.

The second alternative option is the "windshield survey" which is used to determine locations of highly impacted training areas and locate LRAM sites. Fort Riley currently employs this method. The ITAM coordinator estimates that a technician ($38/hr for GS9 Fringe Rate) currently spends approximately 2-3 hours per day driving through the training areas to identify LRAM sites. Using a General Services Administration (GSA) provided $1.24/mi for a truck and assuming an average velocity of 30 mph, this equates to $24,100. Including a labor cost of $24,700, this method of LRAM site identification costs the government $48,800/year/installation. This method is comparable to Scenario 2, which results in a cost of $47,449/yr/installation.

While not indicated in this analysis, the cost of the "windshield survey" is a function of the training intensity being observed. The values stated are for the current training of 1-2 Brigades. As training load increases in coming years, these costs will also increase. While VDMTS implementation does not completely eliminate the need for field validation of these sites, tracking a number of events per year could reduce this cost and free technician time to repair more of these impacted sites. Additionally, the field validations ("windshield surveys") traditionally do not detect all possibly LRAM sites due to lack of visibility (e.g., vegetation or topography preventing identification of highly disturbed sites from a vehicle). Another added benefit that is not quantified in this analysis is the ability to use the VDMTS data for NEPA and ATTACC reporting and assessments.

8 Implementation Issues

8.1 VDMTS acceptance, issues, and alternatives

Once individuals used the VDMTS units and used the data they collected, they were often impressed and excited to implement them into their programs. Initially, the technicians were generally hesitant to commit too much of their time to using the systems. After using the systems once, they were often surprised by the lack of time and effort required to collect the data. At Fort Riley and PTA, the use of the VDMTS system was implemented into the installation proposed ITAM 5-year plans. Staff at a third installation requested a proposal to track additional training events after the ESTCP demonstration project to support an existing research program on base. However despite the installation acceptance of the process, turnover at ITAM and Environmental installation branches may result in VDMTS system implementation issues. Additionally, there seems to be little continuity in programs as this turnover occurs. An original installation staff member may find the VDMTS collected data and analysis invaluable towards their program; however, their replacement may not have the time or desire to learn how the system could support their work.

Currently, the VDM tracking units are custom built by Cybernet Inc. A lower cost alternative (vehicle-tracking system [VTS] unit) without the INS tracking capability can be built using standard commercial off-the-shelf (COTS) components. User manuals for the VDM units are supplied in Appendix C. The factors involved with implementing either system or hiring a regional support center to collect tracking data are summarized in Section 7.3, “Cost analysis and comparison” (p 95). The main driver for these decisions is the availability of in-house labor and capability to perform simple analysis of the vehicle-tracking data.

An additional option for implementation involves using existing military standard systems (Army’s BFT and National Guard’s DFIRST) which obtain vehicle location and time data on live training events for post-event analysis. While this option reduces the labor required for the collection of vehicle positional information, it presents a whole new set of implementation issues. The primary issue involves getting permission to use these data. Some of these data are classified and would need to be declassified prior to obtaining them. Secondly, the quality of the data (positional and

temporal) may not match those validated under this demonstration plan. A study is currently being performed to investigate data quality from these systems compared with the data collected from the VDM and VTS systems.

8.2 Technology transfer and implementation

The demonstration plans outlined multiple methods of tech transfer and implementation to improve military land management decision making. However as mentioned in the previous sections, our installation hosts often found value to the data collected through this work in ways not anticipated. The following section describes some of the different ways the data collected through this project have been used outside the scope of this project.

Fort Benning found value in characterization of vehicle travel and training area use. Discussion with installation staff led to the concept of analyzing vehicle-tracking data to determine distances to RCW habitat. Previous work determined flushing responses to military training at different distances. These data allowed Fort Benning to begin to estimate how much a certain training event could affect populations. Monitoring the vehicles with VDM tracking units was instrumental in gaining the approval of the USFWS to allow increased vehicular traffic around RCW clusters that were due to changes to the POI for the ARC. Coordination with Fort Benning is ongoing to augment an existing research project aimed at investigating heavy maneuver effects on RCWs. These data help quantify and characterize the extent of vehicular training in RCW habitat.

This project enabled support of an Armor School Command sponsored "Good Hope Soil Disturbance Demo" project at Fort Benning. This demonstration informed command on expected soil disturbance from training events in the newly constructed training areas. This study, in turn, gained support by supplying quantitative data on impacts and vehicle maneuvers.

Coordination is ongoing with ESTCP Project RC-200820 to ensure the data collected at Fort Riley and PTA can be used as an input to the Kinematic Wave Rapid Soil Erosion Assessment Model. Vehicle-tracking data (vegetation removal and RD) collected at PTA have been used in the model to improve estimation of vegetation cover maps (bare vs. vegetation). These data can also improve the Digital Elevation Model (DEM) data as a vehicle rut can concentrate overland flow and increase the probability for gully formation.

Data collected from this project are currently informing the model development for an ERDC 6.2 study Optimal Allocation of Land for Training and Non-Training Uses (OPAL). The objective of the OPAL work package is to predict impacts for cumulative military land-use activities and provide optimization routines for military land managers. This informs land management decisions and allows for estimation of past, present, and future impacts given historical and planned land use. All of the separate training events tracked through this study are being combined into a single database. Impacts and training distribution will be characterized be mission type allowing more accurate predictions of impacts from planned training events.

The theoretical models are also being adapted and modified for improvement of vehicle mobility and power requirement models. A US Army Tank Automotive Research, Development and Engineering Center (TARDEC) funded project titled “Advanced Vehicle/Terrain Interaction Modeling to Support Power and Energy Analysis” has incorporated the DW models as well as the soils database generated through this demonstration’s field studies.

As described in this section, this project was successful in going outside of the initial project scope by providing interested parties data and summaries for improved understanding of mission impacts to soil and vegetation. This is partially due to the variety of backgrounds of personnel who were involved with this project. Data and summaries from this project were used to brief the Headquarters, Department of the Army (HQDA) ITAM Program Manager, USFWS regulators at Fort Benning, and training commands. People from varying backgrounds understood how the data collected could be used to inform their land-use and training decisions and model development. Implementation of this technology requires consideration of the information desired and the different options for data collection. Decisions to implement the VDMTS process must take into account the question being asked and resources available to the installation.

9 Conclusions

This project demonstrated and validated the VDMTS system and its components through a series of controlled field studies and live tracking events at Fort Riley, KS, Fort Benning, GA, Eglin AFB, FL and Pohakuloa Training Area, HI.

This demonstration/validation project tested and validated each aspect of the VDMTS process at multiple levels, specifically: accuracy of the hardware and models in combination; durability of the hardware under multiple training events; ease of use of the VDMTS process; and ability to make land-use decisions based on the VDMTS collected and summarized data. The following quantitative metrics were tested to assess each aspect of VDMTS performance: (1) accurate VDMTS hardware measurement of vehicle dynamic properties, (2) accurate VDMTS impact model predictions of site impacts under controlled conditions, (3) accurate VDMTS hardware measurement of vehicle static and dynamic properties, (4) accurate VDMTS model predictions of site impacts during live training, (5) VDMTS hardware durability (in single live training event), (6) VDMTS Hardware durability over 14 live training events, (7) ease of system use, and (8) quality and accuracy of data for land-use decisions.

The following hardware performance metrics 1, 3, and 5-8 were met: . Metrics 2 and 4 (accurate VDMTS impact models predictions in controlled and live events) did not meet the success criteria initially proposed. The demonstrated average error for disturbed width was 14.9 cm and the average error for vegetation removal was -1.8%. These results are comparable with existing site and vehicle-specific empirical model predictions, thus reducing the need to develop models for each site. This validates the use of the theoretical models for impact prediction.

This work concludes that a need exists for a system that can produce data and analyses like the VDMTS, which met most of the established metrics, and —while it failed to meet some metrics— still performed as well as previous methods in characterizing vehicle impacts, reducing the relative cost and time required.

The results of this work clearly show that this technology is valuable in obtaining data to estimate impacts from military training. Through the course of the project, results obtained from this work was used by Integrated Training Area Management (ITAM) program, Environmental, Directorate of Public Works (DPW), and Training groups. Data collected were used in land management and vehicle mobility and power models, and study results also informed training and regulating decisions.

Acronyms and Abbreviations

Term	Definition
2DRMS	Twice Distance Root Mean Square
AAV	Amphibious Assault Vehicle
AFB	Air Force Base
ANSI	American National Standards Institute
APC	Armored Personnel Carrier
ARC	Army Reconnaissance Course
ARRM	Army Range Resource Model
ASABE	American Society of Agricultural and Biological Engineers
ASAE	American Society of Agricultural Engineers
ATTACC	Army Training and Testing Area Carrying Capacity
BFT	Blue Force Tracking
BRAC	Base Realignment and Closure
CEERD	US Army Corps of Engineers, Engineer Research and Development Center
CEP	Circular Error Probable
CERL	Construction Engineering Research Laboratory
CFR	Code of the Federal Regulations
COTS	Commercial Off-The-Shelf
CWA	Clean Water Act
DEM	Digital Elevation Model
DFIRST	Deployable Force-on-Force Instrumented Range System
DGPS	Differential Global Positioning System
DoD	US Department of Defense
DPW	Directorate of Public Works
DW	Disturbed Width
EDYS	Ecological Simulation Modeling
EIS	Environmental Impact Statement
ELVS	Evaluation of Land Value Study
ERDC	Engineer Research and Development Center
ESA	US Endangered Species Act
ESTCP	Environmental Security Technology Certification Program
GIS	geographic information system
GPS	Geographic Positioning System
GPS/INS	Geographic Positioning and Inertial Navigation System
GS	General Schedule
GSA	General Services Administration
HDOP	Horizontal Dilution of Precision

Term	Definition
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
HQDA	Headquarters, Department of the Army
ID	identification
INS	Inertial Navigation System
IS	Impact Severity (Vegetation removal)
ISTVS	International Society for Terrain-Vehicle Systems
ITAM	Integrated Training Area Management
LAV	Light Armored Vehicle
LCTA	Land Condition Trend Analysis
LMTV	Light Medium Tactical Vehicle
LRAM	Land Repair and Maintenance
MEMS	micro electro mechanical systems
MODIS	Moderate Resolution Imaging Spectroradiometer
MTV	Medium Tactical Vehicle
NA	Not Applicable
NATO	North Atlantic Treaty Organization
NEPA	The National Environmental Policy Act
NGA	National Geospatial Intelligence Agency
NPS	Nonpoint Source
NRMM	NATO Reference Mobility Model
NSN	National Supply Number
OMB	Office of Management and Budget
OPAL	Optimal Allocation of Land for Training and Non-Training Uses
OTD	Office of the Technical Director
PI	Principal Investigator
POI	Program of Instruction
PTA	Pohakuloa Training Area
QA/QC	Quality Assurance/Quality Control
RCW	Red-cockaded Woodpecker
RD	Rut Depth
RFMSS	Range Facility Management Support System
RTLA	Range and Training Land Assessment Program
SAE	Society of Automotive Engineers
SAR	SAME As Report
SAT	Satellite
SBIR	Small Business Innovation Research
SD	Secure Digital
SERDP	Strategic Environmental Research and Development Program
SF	standard form

Term	Definition
SMSP II	Soil Moisture Strength Prediction Model, Version II
TACOM	US Army Tank Automotive and Armaments Command
TARDEC	US Army Tank Automotive Research, Development, and Engineering Center
TDR	Time Domain Reflectometry
TES	Threatened and Endangered Species
TIF	Training Impact Factor
TL	Track Length
TMDL	Total Maximum Daily Load
TR	Technical Report
TW	Track Width
US	United States
USA	United States of America
USAWES	US Army Waterways Experiment Station
USB	Universal Serial Bus
USCS	Unified Soil Classification System
USDA	US Department of Agriculture
USFWS	US Fish and Wildlife Service
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
VDM	Vehicle Dynamics Monitor
VDMTS	Vehicle Dynamics Monitoring and Tracking System
VTI	Vehicle Terrain Interface
VTS	Vehicle-Tracking System
WAAS	Wide Area Augmentation System
WWW	World Wide Web

References

Ahlvin, R. B., and P. W. Haley. 1992. NATO reference mobility model edition II, NRMM II user's guide. Technical Report GL-92-19. Vicksburg, MS: US Army Engineer Waterways Experiment Station (USAWES).

Althoff, P. S., and S. J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42(2005):159-176.

Anderson, A. B. 1999. Sensitivity analysis of the army training and testing area carrying capacity (ATTACC) model to user-specified starting parameters. Technical Report CERL TR-99/64. Champaign, IL: Construction Engineering Research Laboratory (CERL).

Anderson, A. B., P. D. Ayers, H. Howard, and K. D. Newlin. 2007a. Vehicle impacts on vegetation cover at Camp Atterbury, IN: Part 1. Initial impacts and vegetation recovery. Proceedings of the Indiana Academy of Science 116(2):126-138.

Anderson, A. B., P. D. Ayers, P. Sullivan, and W. R. Ochsner. 2007b. Vehicle impacts on vegetation cover at Camp Atterbury, IN: Part 2. Predicting impacts of untested vehicles. Proceedings of the Indiana Academy of Science 116(2):139-147.

Anderson, A. B., P. Ayers, A. Palazzo, J. Fehmi, S. Shoop, and P. Sullivan. 2005a. Assessing the impacts of military vehicle traffic on natural areas: Introduction to a special issue of the Journal of Terramechanics and review of the Relevant Military Vehicle Impact Literature. Journal of Terramechanics 42(3-4):143-158.

Anderson, A. B., G. Wang, S. Fang, G. Z. Gertner, B. Güneralp, and D. Jones. 2005b. Assessing and predicting changes in vegetation cover associated with military land-use activities using field monitoring data at Fort Hood, Texas. Journal of Terramechanics 42(3-4):207-229.

Anderson, A. B., P. D. Ayers, G. Wang, G. Z. Gertner, H. R. Howard, S. Fang, and P. Woodford. 2007. Assessing vehicle impacts at multiple scales on US Army installations using Fort Riley, Kansas as an example. In: Innovations in Terrain and Vehicle Systems in the Joint North American, Asia-Pacific ISTVS Conference and Annual Meeting of the Japanese Society for Terramechanics, Fairbanks, AK, 23-26 June 2007. Paper No. 2007-41-0427.

Anderson A. B., L. Chenkin, L. Winters, R. Hunt, C. Couvillon, D. McFerren, S. Sekscienski, and P. Sydelko. 1996. Evaluation of land value study (ELVS)/Army training and testing area carrying capacity (ATTACC). In: Fifth Annual LRAM/ITAM Workshop Proceedings. August 27-29, 1996. LaCrosse, WI, pp 817.

Anderson, A. B., P. D. Ayers, H. R. Howard, P. Sullivan, D. A. Horner, M. Faust and W. R. Ochsner. 2009. Vehicle impacts on vegetation cover at Camp Atterbury, Indiana: Part 3. Predicting cumulative impact of a military training event. Proc. Indiana Acad. Sci. 118(2):114-119.

American Society of Agricultural Engineers (ASAE). 1999. ASAE standard: Procedures for using and reporting data obtained with the soil cone penetrometer. St. Joseph MO: ASAE.

Ayers, P. D., A. B. Anderson and C. Wu. 2005. Analysis of vehicle use patterns during field training exercises. Journal of Terramechanics 42(3-4):321-338.

Ayers, P., H. Howard, A. B. Anderson and Q Li. 2006. Evaluation of low impact military tires. Tire Science and Technology 34(4):256-274.

Bailey, R. G. 1995. Description of the ecoregions of the United States. 2nd ed. rev. and expanded (1st ed. 1980). Misc. Publ. (rev.), Washington, DC: US Department of Agriculture (USDA) Forest Service.

Bussen, P. 2009. Analysis of a rapid soil erosion assessment tool. M.S. Thesis. Manhattan, KS: Kansas State University.

Childress W. M., C. L. Coldren, and T. McLendon. 2002. Applying a complex, general ecosystem model (EDYS) in large-scale land management. Ecological Modeling 153:97-108.

Cybernet Systems. 2004. Enhanced GPS/INS tracking and vehicle dynamics monitoring system. Report for Contract W9132T-04-C-0001. Submitted to CERL 11 November 2004.

Cybernet Systems. 2002. Enhanced accuracy INS/GPS system utilizing low-cost sensors and geophysical models. Final report for contract DACA42-00-C-0042. Submitted to US Army Topographical Engineering Center 31 October 2002.

Demarais, S., D. Tazik, P. Guertin, E. Jorgensen. 1999. Disturbance associated with military exercises. In: L. Walker (ed.). Ecosystems of the world 16, Ecosystems of disturbed ground. Elsevier, New York, pp 385-395.

Foster, J. R., P. D. Ayers, A. M. Lombardi-Przybylowicz and K. Simmons. 2006. Initial effects of light armored vehicle use on grassland vegetation at Fort Lewis, Washington. Journal of Environmental Management 81(2006):315-322.

Grantham, W. P., E. F. Redente, C. F. Bagley, and M. W. Paschke. 2001. Tracked vehicle impacts to vegetation structure and soil erodibility. Journal of Range Management 54:711-716.

Haugen, L. B. 2002. Design and testing of a vehicle tracking system for monitoring environmental impact at US Army training installations. M.S. Thesis, Colorado State University, Fort Collins, CO.

Haugen, L. B., P. D. Ayers, and A. B. Anderson. 2003. Vehicle movement patterns and impact during military training exercises. Journal of Terramechanics 40(2):83-95.

Johnson, F. L. 1982. Effects of tank training activities on botanical features at Fort Hood, Texas. The Southwestern Naturalist 27:309-314.

Jones, A. R., G. B. McKinley, P. W. Richmond, and D. C. Creighton. 2007. A vehicle terrain interface. In Proc. Joint North America, Asia-Pacific ISTVS Conf. and Annual Meeting of the Japanese Society for Terramechanics. International Society for Terrain-Vehicle Systems.

Knapp A. K. and T. R. Seastedt. 1998. Introduction: Grasslands, Konza Prairie and long-term ecological research. In Grassland dynamics, long-term ecological research in tallgrass prairie. New York, NY: Oxford University Press, pp 3-18.

Knowles, T. W. and T. E. Davo. 1997. Land condition trend analysis: Wildlife summaries. Addendum to Land Condition Trend Analysis Program Summary Fort Benning, Georgia: 1991-1995. Fort Benning, GA, USA.

Kogure K, Y. Ohira, and H. Yamaguchi. 1982. A simplified method for the estimation of soil thrust exerted by a tracked vehicle. Journal of Terramechanics 19(3):165–81.

Koolen A. J. and H. Kuipers. Agricultural soil mechanics. Berlin, Germany: Springer; 1983, p 136.

Li Q., P. D. Ayers, and A. B. Anderson. 2007a. Prediction of impacts of wheeled vehicles on terrain. Journal of Terramechanics 44(2007):205-215.

Li, Q., P. D. Ayers, and A. B. Anderson. 2007b. Modeling of terrain impact caused by tracked vehicles. Journal of Terramechanics 44(2007):395-410.

Lui, K, P. Ayers, H. Howard, R. Jones, and A. Anderson. 2010. Prediction of rut depth during military vehicle turning maneuvers using a modified sinkage numeric. Transactions of the ASABE. 53(4):1019-1024.

Milchunas, D. G., K. A. Shultz, and R. B. Shaw. 1999. Plant community responses to disturbance by mechanized military maneuvers. Journal of Environmental Quality 28:1533-1547.

Milchunas, D. G., K. A. Shultz, and R. B. Shaw. 2000. Plant community structure in relation to long-term disturbance by mechanized military maneuvers in a semiarid region. Environmental Management 25:525-539.

Morrison-Saunders, A. and J. Bailey. 2003. Practitioner perspectives on the role of science in environmental impact assessment. Environmental Management 31:683-695.

Nunez, R., R. Jones, and S. Shoop. 2004. High-fidelity ground platform and terrain mechanics modeling for military applications involving vehicle dynamics and mobility analysis. Technical Report A677234. Warren, MI: US Army TACOM Research Development and Engineering Center.

Payne, G., J. Foster, and W. Leininger. 1983. Vehicle impacts on northern Great Plains range vegetation. Journal of Range Management 36:327-331.

Prosser, C. W., K. K. Sedivec, W. T. Barker. 2000. Tracked vehicle effects on vegetation and soil characteristics. Journal of Range Management 53:666-670.

Rice M., P. Ayers, C. Wu, A. Anderson and L. Randolph. 2006. Using GPS and GIS to evaluate vehicle platoon movement for the identification of multi-track traffic during military maneuvers. ASABE Paper No. 06-1044. St. Joseph, MI: ASABE.

Richmond, P. W., R. A. Jones, D. C. Creighton, and R. B. Ahlvin. 2004. Estimating off-road ground contact forces for real time motion simulator. In SAE Commercial Vehicle Symposium. SAE Paper No. 2004-01-2643. Warrendale, PA: SAE.

Rogers, J. L., and W. A. Nicewander. 1988. Thirteen ways to look at the correlation coefficient. The American Statistician 42(1):59-66.

SERDP RC-1102. 1999. Improved units of measure for training and testing area carrying capacity estimation. Arlington, VA: Strategic Environmental Research and Development Program (SERDP). Accessed 24 April 2012, http://www.serdp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Natural-Resources/Watershed-Processes-and-Management/RC-1102

Shaw, R.B, and V. E. Diersing. 1989. Allowable use estimates for tracked vehicular training on Pinon Canyon Maneuver Site, Colorado, USA. Environmental Management 13:773-782.

Shaw, R. B., and V. E. Diersing. 1990. Tracked vehicle impacts on vegetation at the Pinon Canyon Maneuver Site, Colorado. Journal of Environmental Quality 19:234-243.

Snedecor, G. W., and W. G. Cochran. 1980. Statistical methods. Ames IA: The Iowa State University Press.

Sullivan, P. M. and A. B. Anderson. 2000. A methodology for estimating army training and testing area carrying capacity (ATTACC) vehicle severity factors and local condition factors. Technical Report ERDC TR-00-2. Vicksburg, MS: USAWES.

Sullivan, P. M., C. D. Bullock, N. A. Renfroe, M. R. Albert, G. G. Koening, L. Peck, and K. O'Neill. 1997. Soil moisture strength prediction model version II (SMSP II), Technical Report GL-97-15. Vicksburg, MS: USAWES.

Svendsen, N. G., D. J. Koch, H. R. Howard, P. D. Ayers, and A. P. Dain-Owens. 2011. Simulation & modeling for optimal land allocation of military training lands. Paper No. 11111. Proceedings of the 2011 International Symposium on Erosion and Landscape Evolution, Anchorage AK. St. Joseph, MI: ASABE.

Thurow, T. L., S. D. Warren, and D. H. Carleson. 1995. Tracked vehicle traffic effects on the hydrologic characteristics of central Texas rangeland. Transactions of the ASAE 36:1645-1650.

US Air Force. 2010. Integrated natural resources management plan: Eglin AFB, FL.

US Army Environmental Command. 2008. Final environmental impact statement: Permanent stationing of the 2/25th Stryker Brigade Combat Team. Volume 1.

USAWES. 1960. The unified soil classification system. Technical Memorandum No. 3-357. Vicksburg, MS: USAWES.

US Department of the Army. 2002. US Army Garrison Hawaii: 2002-2006 Pohakuloa Training Area integrated natural resources management plan and environmental assessment. US Army Garrison, Hawaii.

Warren, S., H. Mitasova, M. Jourdan, W. Brown, B. Johnson, D. Johnson, P. Julien, L. Mitas, D. Molnar, and C Watson. 2000. Digital terrain modeling and distributed soil erosion simulation/measurement for minimizing environmental impacts of military training. Final Report. Fort Collins, CO: Center for the Ecological Management of Military Lands, Colorado State University.

Wilson, S. 1988. The effects of military tank traffic on prairie: A management model. Environmental Management 12:397-403.

Wong J. 1980. Data processing methodology in the characterization of the mechanical properties of terrain. Journal of Terramechanics 17(1):13–41.

Wong, J. Y. 2001. Theory of ground vehicles. 3d ed. New York, NY: John Wiley & Sons.

Wu, C., P. D. Ayers, and A. B. Anderson. 2004. Evaluation of autonomous and differential GPS for multipass vehicle tracking identification. ASAE Paper No. 04-1061. St. Joseph MI: ASAE.

Wu, C., P. D. Ayers, and A. B. Anderson. 2006. Influence of travel direction on the GPS dynamic accuracy for vehicle tracking. Transactions of the ASAE 49(3):623-634.

Wu, C., P. D. Ayers, and A. B. Anderson. 2007. Validating a GIS-based multicriteria method for potential road identification. Journal of Terramechanics 44(3):255–263

Appendix A: Points of Contact

Point of Contact Name	Organization Name, Address	Phone, Fax, E-Mail	Role in Project
Daniel Koch	ERDC-CERL 2902 Newmark Drive Champaign, IL 61822	217-373-4552 217-373-7266 daniel.j.koch@usace.army.mil	Principal Investigator (PI)
Dr. Paul Ayers	University of Tennessee 2506 E.J. Chapman Drive Knoxville, TN 37996	865-974-4942 865-974-4514 pdayers@utk.edu	Co-investigator
Heidi Howard	ERDC-CERL 2902 Newmark Drive Champaign, IL 61822	217-373-5865 217-373-7266 heidi.r.howard@usace.army.mil	Co-investigator
Gary Siebert	Cybernet Systems Corp. 3885 Research Park Drive Ann Arbor, MI 48108	734-668-2567 x150 734-668-8780 gary@cybernet.com	Co-investigator

Appendix B: List of Vehicles Tracked by Date and Location

Dates	Location	Card #	Vehicle #/ID	Vehicle Type
18-20 Oct 2010	Fort Benning	2	LT 206	Bradley
18-20 Oct 2010	Fort Benning	11	LT 187	Bradley
18-20 Oct 2010	Fort Benning	12	53	Stryker
18-20 Oct 2010	Fort Benning	14	55	Stryker
18-20 Oct 2010	Fort Benning	18	54	Stryker
18-20 Oct 2010	Fort Benning	10	55	Stryker
18-20 Oct 2010	Fort Benning	14	LT 187	Bradley
18-20 Oct 2010	Fort Benning	17	LT 206	Bradley
18-20 Oct 2010	Fort Benning	21	54	Stryker
28-29 Mar 2011	Fort Benning	11	STR01	Stryker
28-29 Mar 2011	Fort Benning	18	LT-159T	Bradley
28-29 Mar 2011	Fort Benning	25	SEP1.1	Abrams
28-29 Mar 2011	Fort Benning	9	LT-159T	Bradley
28-29 Mar 2011	Fort Benning	11	STR01	Stryker
28-29 Mar 2011	Fort Benning	12	LW391	HMMWV
28-29 Mar 2011	Fort Benning	19	SEP1.2	Abrams
1-3 Nov 2011	Fort Benning	2	LW310/LW133	HMMWV
1-3 Nov 2011	Fort Benning	3	STR07	Stryker
1-3 Nov 2011	Fort Benning	5	LW058	HMMWV
1-3 Nov 2011	Fort Benning	8	LW601	HMMWV
1-3 Nov 2011	Fort Benning	9	LW261	HMMWV
1-3 Nov 2011	Fort Benning	11	STR18	Stryker
1-3 Nov 2011	Fort Benning	12	LW057	HMMWV
1-3 Nov 2011	Fort Benning	13	STR05	Stryker
1-3 Nov 2011	Fort Benning	17	LW598	HMMWV
1-3 Nov 2011	Fort Benning	19	LW324	HMMWV
1-3 Nov 2011	Fort Benning	20	LW414	HMMWV
1-3 Nov 2011	Fort Benning	15	STR11	Stryker
1-3 Nov 2011	Fort Benning	4	LW318	HMMWV
1-3 Nov 2011	Fort Benning	21	LW314	HMMWV
1-3 Nov 2011	Fort Benning	116	LW138	HMMWV
1-3 Nov 2011	Fort Benning	111	LW266	HMMWV
1-3 Nov 2011	Fort Benning	114	LW602	HMMWV
1-3 Nov 2011	Fort Benning	102	LW413	HMMWV

Dates	Location	Card #	Vehicle #/ID	Vehicle Type
1-3 Nov 2011	Fort Benning	123	LW247	HMMWV
1-3 Nov 2011	Fort Benning	104	LW131	HMMWV
10-13 Nov 2011	Fort Benning	22	LW310	HMMWV
10-13 Nov 2011	Fort Benning	10	STR07	Stryker
10-13 Nov 2011	Fort Benning	1	LW058	HMMWV
10-13 Nov 2011	Fort Benning	6	LW602	HMMWV
10-13 Nov 2011	Fort Benning	27	LW601	HMMWV
10-13 Nov 2011	Fort Benning	24	LW261	HMMWV
10-13 Nov 2011	Fort Benning	26	STR18	Stryker
10-13 Nov 2011	Fort Benning	29	LW057	HMMWV
10-13 Nov 2011	Fort Benning	108	STR05	Stryker
10-13 Nov 2011	Fort Benning	16	LW598	HMMWV
10-13 Nov 2011	Fort Benning	25	LW324	HMMWV
10-13 Nov 2011	Fort Benning	7	LW414	HMMWV
10-13 Nov 2011	Fort Benning	18	STR11	Stryker
10-13 Nov 2011	Fort Benning	14	LW318	HMMWV
10-13 Nov 2011	Fort Benning	28	LW314	HMMWV
10-13 Nov 2011	Fort Benning	100	LW131	HMMWV
10-13 Nov 2011	Fort Benning	105	LW247	HMMWV
10-13 Nov 2011	Fort Benning	101	LW266	HMMWV
10-13 Nov 2011	Fort Benning	103	LW413	HMMWV
10-13 Nov 2011	Fort Benning	104.2	LW259	HMMWV
10-13 Nov 2011	Fort Benning	116	LW138	HMMWV
10-13 Nov 2011	Fort Benning	111.2	LW310	HMMWV
17-21 Aug 2009	Fort Riley	1	1	MTV
17-21 Aug 2009	Fort Riley	2	2	HMMWV
17-21 Aug 2009	Fort Riley	4	4	HMMWV
17-21 Aug 2009	Fort Riley	5	5	MTV
17-21 Aug 2009	Fort Riley	6	6	HMMWV
17-21 Aug 2009	Fort Riley	9	9	HMMWV
17-21 Aug 2009	Fort Riley	10	10	HMMWV
17-21 Aug 2009	Fort Riley	11	11	HMMWV
17-21 Aug 2009	Fort Riley	12	12	HMMWV
17-21 Aug 2009	Fort Riley	13	13	HMMWV
17-21 Aug 2009	Fort Riley	15	15	MTV
17-21 Aug 2009	Fort Riley	16	16	HMMWV
17-21 Aug 2009	Fort Riley	17	17	MTV
17-21 Aug 2009	Fort Riley	18	18	HMMWV
17-21 Aug 2009	Fort Riley	19	19	MTV
17-21 Aug 2009	Fort Riley	22	22	Buffalo

Dates	Location	Card #	Vehicle #/ID	Vehicle Type
17-21 Aug 2009	Fort Riley	24	24	MTV
17-21 Aug 2009	Fort Riley	25	25	HMMWV
13-15 Jul 2010	Fort Riley	3	3	HMMWV
13-15 Jul 2010	Fort Riley	4	4	HMMWV
13-15 Jul 2010	Fort Riley	5	5	HMMWV
13-15 Jul 2010	Fort Riley	7	7	HMMWV
13-15 Jul 2010	Fort Riley	8	8	HMMWV
13-15 Jul 2010	Fort Riley	9	9	HMMWV
13-15 Jul 2010	Fort Riley	10	10	5 Ton 6x6
10-17 May 2011	Fort Riley	2	FSC-120	HMMWV
10-17 May 2011	Fort Riley	4	FSC-101	HEMTT
10-17 May 2011	Fort Riley	5	FSC-172	LMTV
10-17 May 2011	Fort Riley	10	FSC-52	HEMTT
10-17 May 2011	Fort Riley	6	FSC-102	HEMTT
10-17 May 2011	Fort Riley	7	FSC-51	HEMTT
10-17 May 2011	Fort Riley	4	FSC-161	HMMWV
10-17 May 2011	Fort Riley	5	FSC-80	HEMTT
10-17 May 2011	Fort Riley	9	FSC-172	LMTV
10-17 May 2011	Fort Riley	11	FSC-60	HEMTT
10-17 May 2011	Fort Riley	15	FSC-181	HMMWV
10-17 May 2011	Fort Riley	19	FSC-120	HMMWV
17-22 May 2011	Fort Riley	1	FSC-102	HEMTT
17-22 May 2011	Fort Riley	3	FSC-101	HEMTT
17-22 May 2011	Fort Riley	5.2	FSC-120	HMMWV
17-22 May 2011	Fort Riley	8	FSC-52	HEMTT
17-22 May 2011	Fort Riley	9	FSC-172	LMTV
17-22 May 2011	Fort Riley	8	FSC-80	HEMTT
17-22 May 2011	Fort Riley	107	FSC-172	LMTV
17-22 May 2011	Fort Riley	108	FSC-120	HMMWV
17-22 May 2011	Fort Riley	110	FSC-181	HMMWV
17-22 May 2011	Fort Riley	R06	FSC-60	HEMTT
17-22 May 2011	Fort Riley	R17	FSC-51	HEMTT
6-9 Nov 2009	PTA	18	PTA18	Stryker
6-9 Nov 2009	PTA	17	PTA17	Stryker
6-9 Nov 2009	PTA	19	PTA19	Stryker
24-29 Jan 2010	PTA	4	PTA04	AAV
24-29 Jan 2010	PTA	7	PTA07	AAV
24-29 Jan 2010	PTA	9	PTA09	AAV
24-29 Jan 2010	PTA	14	PTA14	AAV
24-29 Jan 2010	PTA	15	PTA15	AAV

Dates	Location	Card #	Vehicle #/ID	Vehicle Type
24-29 Jan 2010	PTA	17	PTA17	AAV
17-23 Jan 2011	PTA	4	523439	AAV
17-23 Jan 2011	PTA	7	523565	AAV
17-23 Jan 2011	PTA	9	522452	AAV
17-23 Jan 2011	PTA	14	522514	AAV
17-23 Jan 2011	PTA	15	523400	AAV
17-23 Jan 2011	PTA	17	523232	AAV
8-10 Jun 2011	PTA	7	114	AAV
8-10 Jun 2011	PTA	18	115	AAV
13-14 Jun 2011	PTA	7	106	AAV
13-14 Jun 2011	PTA	15	103	AAV
13-14 Jun 2011	PTA	7	110	AAV
13-14 Jun 2011	PTA	10	114	AAV
13-14 Jun 2011	PTA	14	102	AAV
13-14 Jun 2011	PTA	18	101	AAV
16-17 Jun 2011	PTA	4	106	AAV
16-17 Jun 2011	PTA	7	103	AAV
16-17 Jun 2011	PTA	19	110	AAV
16-17 Jun 2011	PTA	7	102	AAV
16-17 Jun 2011	PTA	10	101	AAV
16-17 Jun 2011	PTA	14	R7	AAV (Wrecker)
16-17 Jun 2011	PTA	18	114	AAV

Appendix C: Vehicle Dynamic Monitor User Guide

Vehicle Dynamic Monitor

Intro to VDM installation: GPS connection and mounting procedure

VDM technical instruction

VDM analysis software Instruction

Cybernet Systems Corporation

U.S. Army Corps of Engineering

Questions should be directed toward the contacts listed below:

Trevor Davey
Cybernet Systems Corporation
727 Airport Blvd.
Ann Arbor, MI 48108
734-668-2567 ext. 112
tdavey@cybernet.com

Cybernet Systems Corporation

Gary Siebert
Cybernet Systems Corp.
727 Airport Blvd.
Ann Arbor, MI 48108
Ph (734) 668-2567x150
Fax (734) 668-8780
gary@cybernet.com

Daniel Koch
ERDC-CERL
2902 Newmark Drive
Champaign, IL 61822
Office: 217-373-4552
Cell: 217-637-3689
Fax: 217-373-7251

U.S. Army Corps of Engineering
Construction Engineering
Research Lab

Heidi Howard
ERDC-CERL
2902 Newmark Drive
Champaign, IL 61822
Office: 217-373-5865
Cell: 217-377-8504
Fax: 217-373-7251

Table of Contents

Introduction to the VDMTS Process

The Vehicle Dynamics Monitoring and Tracking System (VDMTS) can be used to assess and predict military vehicle maneuver training impacts for use in land management decision-making processes and National Environmental Policy Act (NEPA) analyses. The approach spatially characterizes short-term, direct impacts resulting from vehicles by monitoring individual vehicle locations and operating characteristics (i.e. turning radius and velocity). Vehicle impact models are used to predict area impacted, vegetation loss, and rut depth, and are based on vehicle operating characteristics and location. Analysis routines are used to summarize use patterns and the severity of cumulative impacts.

The VDMTS process consists of three components: 1) vehicle impact models, 2) vehicle tracking hardware and software, and 3) vehicle tracking data analysis. This document is a User's Manual for the Vehicle Dynamic Monitor (VDM): the hardware and software component of the VDMTS. It contains information on data collection processes, maintaining the hardware, operating the software, and technical information regarding the data collected.

The vehicle tracking hardware and software measure vehicle kinematics, dynamics, and other parameters of interest that enable accurate modeling of environmental impact. Innovative sensor fusion software combines data from these sensors to provide position information even during GPS outage. The system thereby provides vehicle dynamics data and positional information at all times, even when GPS is unavailable. The VDMTS has the capability to record the vehicle dynamics tagged with position information for post-mission analysis. Vehicle tracking visualization software resides on a user's desktop that provides simple visual access to the VDMTS data within a GIS environment.

Setting up the Vehicle Dynamic Monitor (VDM)

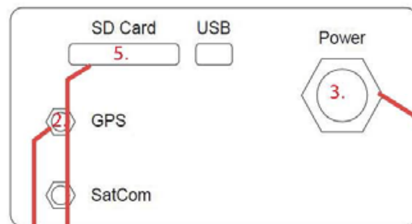
Equipment

The VDM comes packaged in a Pelican Case. It includes the following components:

1.	VDM Module*
2.	Battery*
3.	GPS Antenna*
4.	SD Card*
5.	Power/Charging Cable*
6.	Pelican Case
7.	Battery Charger

**These items are all internal to the Pelican Case.*

Connecting the Device



Upon receiving the VDM these steps should be followed before use:

1.	Verify that the toggle switch is in the "OFF" position
2.	Verify that the GPS antenna connection is tight
3.	Verify that the power cable is properly connected to the VDM
4.	Connect the red wire of the battery/charging cable to the positive terminal of the battery
5.	Verify that the SD card is properly inserted into the VDM
6.	Charge the battery

Mounting the VDM

The VDM should be mounted securely to the test vehicle. It must always be mounted with one axis parallel to the vertical's axis of forward motion. **Figure 2** is a diagram of good vs. bad mounting orientations.

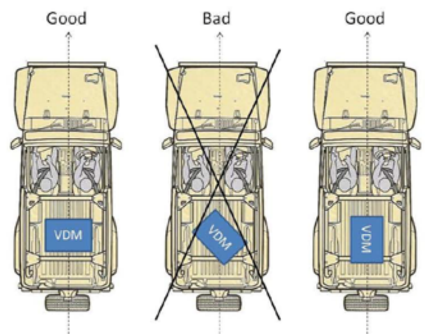


Figure 2: good vs. bad mounting orientation

It does not need to be parallel with the ground. Mounting the VDM on an angle is acceptable and an example can be seen in **Figure 3**. Always note the axiz of vehicle movement, for future use in the VDM analysis software. (See figure 7. on page 8)

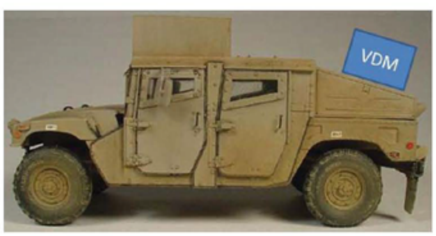
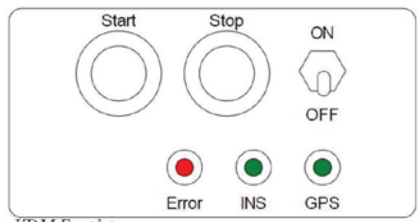


Figure 3: Mounting the VDM at an Angle

Turning on and Operating the VDM module

The Vehicle Dynamic Monitor (VDM) is a small electronic device with GPS and internal sensors. The VDM unit logs sensor data along with GPS position to a removable Secure Digital Card (SD Card). Make sure to delete all Log files from the SD card. For a new SD card make sure the SD card is empty and formatted. If not follow the manufacturer's instruction for formatting the SD card. Note only the standard FAT file system is supported.

The VDM unit has 2 operational modes: **Auto Logging Mode** and **Manual Mode.**



VDM Faceplate

Auto Logging Mode (default)

1. To power up the VDM toggle the power switch to the on position. The GPS, INS, and Error LEDs will come on momentarily and then will turn off.
2. Once the system has booted the unit will then enter motion sensing sleep mode.
3. When vehicle motion (start of the engine) has been detected the unit will wake up and begin to log data.
4. Let the vehicle idle for 1 minute before driving. This will allow the GPS to get a position fix and for the VDM to self calibrate.
5. While the unit is logging the INS LED will blink rapidly and the GPS LED will

blink on and off slowly while waiting for a GPS fix. When the GPS is receiving position fixes the GPS LED will blink on quickly.

6. If the vehicle motion stops the VDM will stop logging and go back into motion sensing sleep mode.
7. At any time during the logging period the user can put the VDM back into motion sensing sleep mode by pressing and releasing the Stop button.
   NOTE: At this point the unit will begin logging data again unless the Stop button is pressed a second time within 3 seconds to power the unit down.
8. To power down the VDM, make sure that it is not logging. All LEDs will be off in this situation. Next, press the Stop button and verify that the Error LED blinks 4 times. Toggle the power switch to the off position.

Manual Logging

At any time while in Auto Logging Mode the VDM can be forced to log data manually.

1. Pressing and releasing the Start button will force the VDM to log data manually. Once manual logging has been initiated the unit will only stop logging with use of the Stop button.
2. Pressing and releasing the Stop button will stop logging and return the VDM to motion sensing sleep mode.

SD Card Reader Mode

The VDM can be started as a SD card reader mode. This will allow for retrieval of the data through the USB port and eliminate the need to remove the SD card.

1) Before powering up the unit press and hold the Stop button.
2) Continue to hold the Stop button and toggle the power switch to the on position.
3) The VDM will enter SD card reader mode and will turn on the INS and GPS LEDs when the USB cable is connected and configured correctly.
4) The user can now read and write to the SD card from the PC.
5) To power down the VDM, follow the PC's steps to safely remove a USB device. When the device is safe to remove, disconnect the USB cable and toggle the power switch to the off position.

If, at any point in time the Error LED turns on please refer to the troubleshooting section.

Verifying the data / Shutting down the VDM

To verify logging after the VDM has been started, start the vehicle in which the VDM is installed. The LEDs should perform as described in the "Operational Summary" (Note when used in a pelican case the case must be opened to view the LEDs).

To power down the VDM, make sure that it is not logging (Press and release the Stop button if it is). Verify all LEDs are off. Next, press the Stop button and verify that the Error LED blinks 4 times.

Toggle the power toggle switch to the "OFF" position.

Downloading Data

There are two ways to access the VDM log files:

1. By removing the secure digital card and **2.** through a USB connection to the PC. To access the log files via the SD card you will need a SD card reader. To access the log files via USB you will need a USB Type A to mini-USB Type B cable (not included).

Via SD Card

1. If the VDM module is powered on follow the instructions to power down the VDM module.

2. Once the VDM is powered down press the SD card in and it will automatically eject itself from the VDM.

3. Place the SD card in a SD card reader and Copy, Move, Manipulate, and Delete the log files as required.

4. Return the SD card to the VDM for further data logging.

Via USB

1. The VDM must be powered up in the "SD Card Reader Mode."

2. Plug in the USB cable and navigate to the desired directory. Copy, Move, Manipulate, and Delete the log files as required.

3. Request a safe removal of the hardware from the operating system.

4. When it is safe to remove the hardware, the VDM can be disconnected and power down by putting the toggle switch into the "OFF" position.

Charging the Battery Module

1. Toggle the power switch to the "OFF" position

2. Connect the battery charger to a 120VAC power outlet. As shown in Figure 4

3. Connect the battery charger jack to the battery charging cable plug.

4. Verify the charging indicator is solid Red or Green. An LED status chart can be seen in Figure 5.

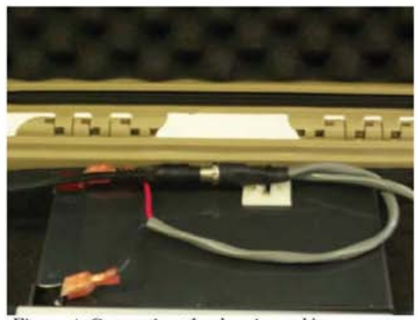
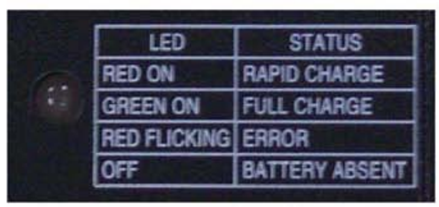


Figure 4. Connecting the charging cable



LED	STATUS
RED ON	RAPID CHARGE
GREEN ON	FULL CHARGE
RED FLICKING	ERROR
OFF	BATTERY ABSENT

Figure 5. Battery Charger LEDStatus Chart

Error Indications

Errors are indicated with the Error LED.

Indication	Error
ON	There is no SD card connected to the VDM
1 Blink per second	
2 Blinks per second	
3 Blinks per second	
4 Blinks per second	

Technical support and product service

If you experience difficulty getting your VDM operating properly please contact Cybernet's Technical support. Our Technical staff is available by phone 9:00-5:00 Eastern Standard time at 734.668.2567 or by e-mail at support@cybernet.com

Please refer to your product technical support agreement if support beyond the initial support period.

On-Line Support

On-Line support is available through the following services.
E-mail: support@cybernet.com
Website: http://www.cybernet.com/VDM

Vehicle Dynamic Monitor (VDM) Technical Instruction

Log File Name

The VDM generates a new log file ever time it wakes and begins logging. The log file name format follows, where xxxx is a sequential number corresponding to the number of files that have been created.

```
LOG_xxxx.VDM
```

An example set of files follows:

```
LOG_0001.VDM
LOG_0002.VDM
LOG_0003.VDM
LOG_0004.VDM
```

Log File Header

Each log file begins with a header attachment that provides information about how the data was collected. An example header can be seen below. The first line is the software version identifier. The second line is a serial number that identifies what VDM was used to collect the data. Finally, the third line indicates whether the VDM started collecting data using its automatic feature or by depression of the manual start button.

```
#VDM Logger : Ver1.1
S00000002
#VDM Auto Start
```

VDM Protocol

The VDM records inertial and temperature data at a rate of 100Hz and GPS data at 1 Hz. A sample section of data can be seen below. The inertial string starts with an 'I' (for inertial) and the GPS starts with a 'G' (for GPS).

```
I0004D26E$S8003$ABFFC$B000C$C8019$DBFF5$E80E7$FBF44$G8022$H80C0$IBF2F$J800C$K8749
I0004D278$S87FF$A8002$BBFFA$C8016$DBFF1$E80F7$FBF42$G801E$H80BD$IBF2F$J800C$K8749
I0004D282$S87FD$A800A$BBFFE$C801A$DBFE9$E80F2$FBF40$G801B$H80BC$IBF30$J800D$K8748
I0004D28B$S87FE$ABFFC$B8004$C8030$DBFEA$E80EC$FBF3D$G8023$H80C4$IBF29$J800D$K8748
I0004D295$S87FE$A8009$BBFFF$C802F$DBFF3$E80E0$FBF3D$G802A$H80CD$IBF20$J800C$K8748
I0004D29F$S8002$ABFF2$B0004$C8041$DBFFB$E80E0$FBF41$G802A$H80CD$IBF20$J800C$K8749
G0004D255GetNMEA$GPGGA,190050.00,4213.92259,N,08344.51152,W,1,08,1.07,259.5,M,-34
I0004D2A9$S87FB$A8002$B8003$C8020$DBFFD$E80EA$FBF41$G8026$H80C7$IBF2A$J800D$K8748
I0004D2B2$S87FE$A8001$BBFF8$C800C$DBFF7$E80EB$FBF42$G8023$H80C4$IBF2A$J800C$K8747
I0004D2BC$S8002$A8020$BBFEF$C8004$DBFF3$E80FA$FBF38$G801E$H80BE$IBF30$J800D$K874A
I0004D2C6$S87FC$A8004$B0006$C801D$DBFED$E80EF$FBF3B$G8020$H80BF$IBF32$J800D$K874C
```

Inertial String

```
I0004D2D0$S87FF$A8022$BBFFA$C8021$DBFF3$E80F4$FBF3B
-|------||----------------------------------------|
|     |              |
|     |              +-----I3M data packet (less CR/LF)
|     +---------Time stamp of packet in millisecond
--------- -------------------Packet type 'I' - I3M
```

The Inertial string is broken down above. All the data is provided in ASCII form, but represents a Hexadecimal number. It begins with a string identifier (I) followed by a 4 Byte timestamp where each Least Significant Bit (LSB) = 1 millisecond from the power up of the VDM. The timestamp is in unsigned hexadecimal format. For example, 00028DFB would equal 167,419 milliseconds. The timestamp is followed by 12 packets of data that provide the raw inertial data. Each packet begins

with a start character ($) and a packet identifier. 2 Bytes of measurement data will follow the packet identifier. The measurement data is in 2's compliment format as well as a New Data and Error indicator. The message format for the inertial packet can be seen in Figure 1. The message format for the temperature packet can be seen in Figure 2.

Inertial Packet Format															
Bit Position															
15	15	13	12	11	10	9	8	7	6	5	4	3	2	1	0
New Data Indicator	Error Indicator	14-bit Measurement in 2's Compliment Format													

Figure 1: Inertial Packet Message Format

Temperature Packet Format															
Bit Position															
15	15	13	12	11	10	9	8	7	6	5	4	3	2	1	0
New Data Indicator	Error Indicator	X	X	12-bit Measurement in 2's Compliment Format											

Figure 2: Temperature Packet Message Format

To convert the data into real world values the conversion scalars in Figure 3 need to be used. Some example conversions follow.

Data Type	Scale		Note
Gyroscope	0.05	°/s/LSB	
Accelerometer	3.33	mg/LSB	
Magnetometer	0.5	mgauss/LSB	
Temperature	0.14	°C/LSB	25°C = 0x0000
Supply	2.42	mV/LSB	
Analog	0.81	mV/LSB	

Figure 3: Conversion Scalars for Inertial String

Sample Conversions:

$BB209 = -178.75 °/s
$E80F2 = 0.806 g
$H80BC = 0.094 gauss
$J800D = 26.82 °C
$S87FE = 4.951 V
$IBF30 = -0.1 gauss
I0004D295 = 5.27 minutes

INERTIAL STRING		
Byte	Data	Data Description
0	I	INS Identifier
1-8	xxxxxxxx	Time Stamp in milliseconds from power up
9	$	Packet Separator
10	S	Supply Voltage Identifier
11-14	xxxx	LSB 14 bits, 2's Compliment
15	$	Packet Separator
16	A	X-Axis Gyroscope Identifier
17-20	xxxx	LSB 14 bits, 2's Compliment
21	$	Packet Separator
22	B	Y-Axis Gyroscope Identifier
23-26	xxxx	LSB 14 bits, 2's Compliment
27	$	Packet Separator
28	C	Z-Axis Gyroscope Identifier
29-32	xxxx	LSB 14 bits, 2's Compliment
33	$	Packet Separator
34	D	X-Axis Accelerometer Identifier
35-38	xxxx	LSB 14 bits, 2's Compliment
39	$	Packet Separator
40	E	Y-Axis Accelerometer Identifier
41-44	xxxx	LSB 14 bits, 2's Compliment
45	$	Packet Separator
46	F	Z-Axis Accelerometer Identifier
47-50	xxxx	LSB 14 bits, 2's Compliment
51	$	Packet Separator
52	G	X-Axis Magnetometer Identifier
53-56	xxxx	LSB 14 bits, 2's Compliment
57	$	Packet Separator
58	H	Y-Axis Magnetometer Identifier
59-62	xxxx	LSB 14 bits, 2's Compliment
63	$	Packet Separator
64	I	Z-Axis Magnetometer Identifier
65-68	xxxx	LSB 14 bits, 2's Compliment
69	$	Packet Separator
70	J	Temperature Identifier
71-74	xxxx	LSB 12 bits, 2's Compliment
75	$	Packet Separator
76	K	Analog Channel Identifier
77-80	xxxx	LSB 12 bits, 2's Compliment
81	CR	Carriage Return
82	LF	Line Feed

Figure 4: Inertial String Identifier

GPS String

```
G0004D255GotNMEA$GPGGA,190050.00,4213.92259,N,08344.51152,
-|------||----------------------------------------------|
|  |                              |
|  |                              +------GPS message (GGA)
|  +--------------------------------Time stamp of packet in milliseconds
+-----------------------------------------------Packet type 'G' - GPS
```

The GPS string is broken down in Figure 5. It is the Global Positioning System Fix Data (GGA) string that provides 3D location and accuracy data. It is part of the National Marine Electronics Association (NMEA) protocol standard. All the data is provided in ASCII format. It begins with a string identifier (G) followed by a 4 Byte timestamp where each Least Significant Bit (LSB) = 1 millisecond from the power up of the VDM. The timestamp is in unsigned hexadecimal format. The timestamp is followed by a message identifier (GotNMEA) and then the GGA string starting with the string identifier ($GPGGA).

GPS STRING		
Byte	**Data**	**Data Description**
0	G	GPS Identifier
1-8	xxxxxxxx	Time Stamp in milliseconds from power up
9-15	GotNMEA	Message Identifier
16-21	$GPGGA	Message Identifier
22	,	Packet Separator
23-31	hhmmss.ss	Coordinated Universal Time (UTC)
32	,	Packet Separator
33-42	ddmm.mmmmm	Latitude, Degrees + minutes
43	,	Packet Separator
44	N/S	North/South Indicator
45	,	Packet Separator
46-56	dddmm.mmmmm	Longitude, Degrees + minutes
57	,	Packet Separator
58	E/W	East/West Indicator
59	,	Packet Separator
60	x	Position Fix Status Indicator
61	,	Packet Separator
62, 63	xx	Satellites Used, Range 0 to 12
64	,	Packet Separator
65-68	x.xx	Horizontal Dilution of Precision
69	,	Packet Separator
70-74	xxx.x	Mean Sea Level (MSL) Altitude
75	,	Packet Separator
76	M	Units, Meters
77	,	Packet Separator
78-81	xx.x	Geoid Separation
82	,	Packet Separator
83	M	Units, Meters
84	,	Packet Separator
85	empty field	Time Between Differential Corrections
86	,	Packet Separator
87	empty field	Differential Reference Station ID
88-90	*xx	Checksum
91	CR	Carriage Return
92	LF	Line Feed

Figure 5: GPS String Identifier

VDM Axes Orientation

The VDM axes orientation can be seen Figure 6. When it is placed inside the Pelican Case the orientation changes and can be seen in Figure 7.

Figure 6: VDM Axes Orientation

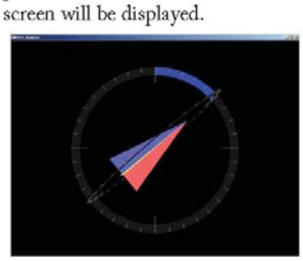
Figure 7: Axes Orientation of the VDM in Pelican Case

Vehicle Dynamic Monitor (VDM) Software Instruction

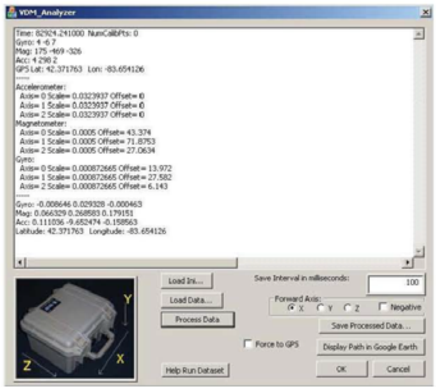
Step-by-step guide to using the VDM Analysis software

1. **Open the VDM Analysis software.** Navigate to the location of the VDM Analysis software and run the program.
2. **Load the configuration file.**
   a) Click the "Load Ini…" button.
   b) Navigate to the location of the "con fig.ini" that corresponds to the VDM and click "Open". The default file can be found in the storage location of the "VDM Analysis" software.
3. **Load the data file that was collected by the VDM.**
   a) Click the "Load Data…" button.
   b) Navigate to the location of the "LOG_ xxxx.VDM" that was collected by the VDM and click "Open".
4. **Select the forward axis of the VDM.**
   a) This is determined by how the VDM was mounted on the vehicle during data collection. Use the visual indicator to determine the forward axis.

   b) Select the "X", "Y", or "Z" forward axis. Then select if the negative axis is pointing forward. Note: In the diagram, the end with the arrow is the positive direction.
5. **Determine if the output data needs to be forced to the GPS data. (Optional)** The "Force to GPS" option will use every GPS position update to help increase the accuracy of the inertial data. It will alter the inertial data algorithms to force the output to the absolute GPS position. In other words, it will make sure that the inertial data that is collected between two GPS points starts at the first GPS point and will end at the second GPS point. If this option is not selected then the inertial data will have the potential of ending at a different position than the GPS data
6. **Process the data.**
   a) Click on the "Process Data" button and wait for the VDM Analysis software to perform the calculations. The following screen will be displayed.



b) When the processing is complete the arrow will have stopped moving and the software screen will look as follows.



7. **Save the processed data.**
   a) Click the "Save Processed Data…" button.
   b) Name the file as desired and navigate to the location where you want to store it on the hard drive.
8. **Display the path on Google Earth** (Optional)
   a) Click the "Display Path in Google Earth" button and the software will present the path in Google Earth. The red line is the GPS path and the blue line represents the inertial data.
   b) Note: Google Earth must be installed for this function to work.

Explanation of the Processed Data File

A sample output file can be seen on the next page An explanation of the file data follows:

Time: The number of seconds from 12:00 Am., Coordinated Universal Time (UTC)

UTC: Coordinated Universal Time in hours (first 2 digits), minutes (second 2 digits), seconds (third 2 digits), milliseconds (last 3 digits)

Count: the number of samples that were averaged into the data point

Lat: Latitude in degrees

Lon: Longitude in degrees

Ax: Acceleration in the x-axis (m/s2)

Ay: Acceleration in the y-axis (m/s2)

Az: Acceleration in the z-axis (m/s2)

Mx: X-axis magnetometer, not scaled at this time

My: Y-axis magnetometer, not scaled at this time

Mz: Z-axis magnetometer, not scaled at this time

Gx: Angular rate in the x-axis (m/s)

Gy: Angular rate in the y-axis (m/s)

Gz: Angular rate in the z-axis (m/s)

RawA: Raw data from the accelerometers [X-axis, Y-axis, Z-axis]

RawM: Raw data from the magnetometers [X-axis, Y-axis, Z-axis]

RawG: Raw data from the gyroscopes [X-axis, Y-axis, Z-axis]

GGA string: If a GPS signal was captured during the data point development then the GGA string has been attached for information on the signal quality

Time=	53071.002	UTC=	144431.002	Count=	1	Lat=	39.301023	Lon=	-96.923883	Ax=	-1.015082	Ay=	0.775218	Az=	-13.006616	Mx=	0.052058	My=	0.069461	Mz=	0.254243	Gx=	-0.033306	Gy=	0.032852	Gz=	-0.245014
Time=	53071.11	UTC=	144431.11	Count=	6	Lat=	39.301023	Lon=	-96.923883	Ax=	-1.029255	Ay=	0.948112	Az=	-11.626783	Mx=	0.052407	My=	0.068247	Mz=	0.253036	Gx=	-0.0342	Gy=	0.035356	Gz=	-0.252446
Time=	53071.215	UTC=	144431.215	Count=	12	Lat=	39.301021	Lon=	-96.923883	Ax=	-0.624841	Ay=	0.203648	Az=	-8.522428	Mx=	0.053496	My=	0.067085	Mz=	0.251147	Gx=	-0.032507	Gy=	0.037859	Gz=	-0.268015
Time=	53071.325	UTC=	144431.325	Count=	11	Lat=	39.301021	Lon=	-96.923883	Ax=	-1.15627	Ay=	-0.687237	Az=	-7.443141	Mx=	0.055394	My=	0.068778	Mz=	0.252711	Gx=	-0.028519	Gy=	0.032889	Gz=	-0.280817
Time=	53071.435	UTC=	144431.435	Count=	11	Lat=	39.301023	Lon=	-96.923883	Ax=	-1.41662	Ay=	0.193314	Az=	-11.019666	Mx=	0.056215	My=	0.068712	Mz=	0.254064	Gx=	-0.03299	Gy=	0.031634	Gz=	-0.293991
Time=	53071.545	UTC=	144431.545	Count=	11	Lat=	39.301024	Lon=	-96.923882	Ax=	-1.441775	Ay=	1.116929	Az=	-11.98369	Mx=	0.056074	My=	0.067268	Mz=	0.252355	Gx=	-0.040016	Gy=	0.037623	Gz=	-0.306112
Time=	53071.645	UTC=	144431.645	Count=	10	Lat=	39.301024	Lon=	-96.923882	Ax=	-0.551895	Ay=	0.564345	Az=	-9.697136	Mx=	0.055387	My=	0.06707	Mz=	0.251444	Gx=	-0.039632	Gy=	0.043336	Gz=	-0.316323
Time=	53071.746	UTC=	144431.746	Count=	10	Lat=	39.301024	Lon=	-96.923882	Ax=	-0.804421	Ay=	-0.432352	Az=	-7.095303	Mx=	0.054793	My=	0.06802	Mz=	0.254477	Gx=	-0.034831	Gy=	0.041001	Gz=	-0.326214
Time=	53071.859	UTC=	144431.859	Count=	10	Lat=	39.301025	Lon=	-96.923882	Ax=	-1.118308	Ay=	-0.629448	Az=	-8.853902	Mx=	0.055599	My=	0.068196	Mz=	0.257629	Gx=	-0.034919	Gy=	0.040347	Gz=	-0.336729
Time=	53071.965	UTC=	144431.965	Count=	12	Lat=	39.301026	Lon=	-96.923881	Ax=	-1.121329	Ay=	0.617131	Az=	-12.49672	Mx=	0.054747	My=	0.065918	Mz=	0.255979	Gx=	-0.042551	Gy=	0.045597	Gz=	-0.348113
Time=	53072.066	UTC=	144432.066	Count=	10	Lat=	39.301027	Lon=	-96.923881	Ax=	-1.02871	Ay=	0.968229	Az=	-10.8295	Mx=	0.054103	My=	0.062805	Mz=	0.252941	Gx=	-0.048888	Gy=	0.049828	Gz=	-0.358293
Time=	53072.175	UTC=	144432.175	Count=	11	Lat=	39.301027	Lon=	-96.923881	Ax=	-0.569014	Ay=	0.018745	Az=	-7.866904	Mx=	0.05354	My=	0.061258	Mz=	0.252083	Gx=	-0.046158	Gy=	0.05025	Gz=	-0.368344
Time=	53072.276	UTC=	144432.276	Count=	10	Lat=	39.301028	Lon=	-96.92388	Ax=	-1.061415	Ay=	-0.805948	Az=	-7.804015	Mx=	0.055682	My=	0.063022	Mz=	0.252084	Gx=	-0.040757	Gy=	0.0474	Gz=	-0.378805

RawA=[	106830	-159157	5689065	]RawM=[	-79412	574049	-643573	]RawG=[	-99657	216245	-484066	]	GGA=		
RawA=[	180309	-156579	4903759	]RawM=[	-78800	579149	-639807	]RawG=[	-9255	238861	-439304	]	GGA=	G0000CAD0GotNMEA:	GPGGA,144431.00,3918.06126,N,09655.43306,W,1,7,1.32,413.6,M,-27.7,M,,
RawA=[	224169	303017	3319562	]RawM=[	-75645	570085	-644702	]RawG=[	-6980	336421	-462734	]	GGA=		
RawA=[	-247413	491854	3961497	]RawM=[	-68532	570745	-648806	]RawG=[	-74836	287678	-478886	]	GGA=		
RawA=[	-391285	-58688	4680502	]RawM=[	-70862	578409	-646270	]RawG=[	-116493	204942	-449401	]	GGA=		
RawA=[	61851	-395199	5604484	]RawM=[	-72901	574249	-637838	]RawG=[	-53383	194747	-449335	]	GGA=		
RawA=[	116494	-3588	3891546	]RawM=[	-75637	572178	-649198	]RawG=[	19448	299815	-442511	]	GGA=		
RawA=[	-63158	487965	2706045	]RawM=[	-62993	573142	-661874	]RawG=[	-36557	285014	-446919	]	GGA=		
RawA=[	69103	236505	4891838	]RawM=[	-72695	580509	-654329	]RawG=[	-122212	193672	-454645	]	GGA=		
RawA=[	46879	-270021	5298544	]RawM=[	-70779	586526	-644245	]RawG=[	-134239	213369	-441710	]	GGA=		
RawA=[	171294	-199011	4401135	]RawM=[	-73448	592523	-643062	]RawG=[	-33718	249125	-444658	]	GGA=		
RawA=[	270527	598197	3378515	]RawM=[	-71520	583192	-645127	]RawG=[	16201	314629	-443029	]	GGA=		
RawA=[	-230074	620269	4044364	]RawM=[	-72284	573846	-641126	]RawG=[	-59823	281176	-457929	]	GGA=		

Appendix D: VDMTS Evaluation Form

Component of VDMTS process	Rating (1-10 where 1 is difficult and 10 is no issues)	Comments
Ease of System Use		
Operation of vehicle-tracking hardware		
Mounting and dismounting of hardware		
Hardware maintenance (e.g., charging/replacing batteries, data card replacement, etc.)		
Downloading data		
Checking data on computer for errors and completeness		
Processing raw data files		
Processing data to determine vehicle velocity and turning radius		
Using vehicle impact models for prediction of impacts		
Analyzing impact data for site-specific summaries		
Quality and Accuracy of Data for Land-Use Decisions		
Data collected is of value for decision making		
Maps produced from data aid in visualization and analysis of vehicle use patterns and associated impacts		
Comments (Please add any additional comments about use of the system here):		

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
12-06-2012	Final	

4. TITLE AND SUBTITLE
Vehicle Dynamics Monitoring And Tracking System (VDMTS):
Monitoring Mission Impacts In Support Of Installation Land Management

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT

6. AUTHOR(S)
Daniel J. Koch, Paul D. Ayers, Heidi R. Howard, and Gary Siebert

5d. PROJECT NUMBER
ESTCP

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)
PO Box 9005,
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-12-11

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program (ESTCP)
901 North Stuart Street
Suite 303
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Vehicle Dynamics Monitoring and Tracking System (VDMTS) has three components: (1) vehicle impact models, (2) vehicle-tracking hardware and software, and (3) vehicle-tracking stat analysis. The vehicle-tracking approach was used to predict impacts associated with military and vehicle maneuver training. These dynamic characteristics are used to predict area impacted, vegetation loss, and rut depth based on vehicle type and location. These results are then summarized to characterize training land-use patterns and quantify the severity of the training impacts. This demonstration/validation project tested and validated each aspect of the VDMTS process. In multiple levels, it tested and demonstrated the accuracy of the hardware and models in combination, the durability of the hardware under multiple training events, the ease of use of the VDMTS process, and the ability to make land-use decisions based on the VDMTS collected and summarized data. The document provides the lessons learned from the demonstration and provides information on implementation strategies and options.

15. SUBJECT TERMS
military vehicle impacts, vegetation removal, soil erosion, GPS, training land management

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified	SAR	146	